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MONOGRAPHS ON MINERAL RESOURCES
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PREPARED UNDER THE DIRECTION OF THE
MINERAL RESOURCES COMMITTEE OF THE
IMPERIAL INSTITUTE WITH THE ASSISTANCE
OF THE SCIENTIFIC AND TECHNICAL STAFF

NICKEL ORES

BY W. G. RUMBOLD

SCIENTIFIC AND TECHNICAL DEPARTMENT, IMPERIAL INSTITUTE

WITH A MAP



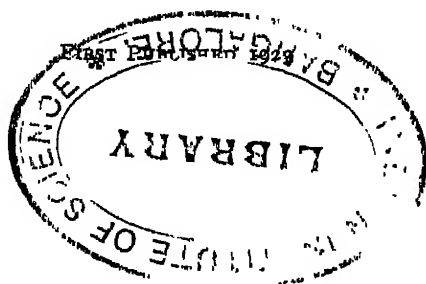
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Important minerals from within the Empire are exhibited in the respective Courts of the Public Exhibition Galleries, and also in the Mineral Reference Collections of the Institute.

A special staff is engaged in the collection, critical revision and arrangement of all important information respecting supplies of minerals especially within the Empire, new methods of usage and other commercial developments.

Articles on these and related subjects are periodically published in the *Bulletin of the Imperial Institute*, and monographs on special subjects are separately published under the direction of the Committee on Mineral Resources.

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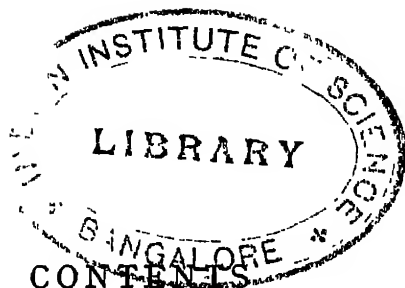
THE Mineral Resources Committee of the Imperial Institute has arranged for the issue of this series of Monographs on Mineral Resources in amplification and extension of those which have appeared in the *Bulletin of the Imperial Institute* during the past fifteen years.

The Monographs are prepared either by members of the Scientific and Technical Staff of the Imperial Institute, or by external contributors, to whom have been available the statistical and other special information relating to mineral resources collected and arranged at the Imperial Institute.

The object of these Monographs is to give a general account of the occurrences and commercial utilization of the more important minerals, particularly in the British Empire. No attempt has been made to give details of mining or metallurgical processes.

HARCOURT,
Chairman, Mineral Resources Committee.

IMPERIAL INSTITUTE, LONDON, S.W.7
July 1920,



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NICKEL ORES: THEIR OCCURRENCE, CHARACTERS AND USES

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NICKEL ORES

CHAPTER I

NICKEL ORES: THEIR OCCURRENCE, CHARACTERS AND USES

INTRODUCTION

THE element nickel was discovered by Cronstedt in 1751 in an ore from Helsingland, Sweden, and was found by him later in niccolite, an arsenide of nickel.

The nickel industry is of comparatively recent date. Although alloys of nickel have been found as Bactrian coins of the year 235 B.C. and ancient Chinese alloys of unknown age containing nickel and copper exist, the metal itself has only been produced on any considerable scale since the early part of the nineteenth century. Indeed, until after the discovery of the New Caledonian nickel deposits (about 1890) nickel was regarded as a somewhat rare metal, and its high cost prohibited its use except for a few special purposes.

The progress of the industry in later years is indicated by the fact that whereas the world's total production of metallic nickel for the year 1900 was given as 7,526 metric tons [1/p. 501], the production of Canada alone, estimated at 80 to 85% of the world's output, for 1918 amounted to 48,886 short tons [2/p. 27].

As to the many uses for nickel, these are referred to in some detail at a later stage, but it is stated that upwards of 75% of the total output is employed in the production of the various kinds of nickel-steel alloys known under the general term of "nickel steel."

The addition of nickel in the manufacture of steel imparts

various special properties to the product, depending upon the proportion in which it is added, and also as to whether one or more of the elements, manganese, chromium, tungsten, molybdenum, vanadium and titanium enter into the composition of the steel alloy. When nickel alone is added to an ordinary carbon steel in small proportions, it largely increases its tensile strength and elastic limit. As an example, it might be mentioned that it has been calculated from comparative tests that by using a steel containing from 3 to 4% nickel, instead of an ordinary carbon steel, for the principal members of a steel bridge, a saving, in weight up to 25%, and in cost of 17%, could be effected [3/p. r66].

The value of nickel steels in industrial engineering is rapidly becoming more appreciated, and it is safe to anticipate a progressive increase in their employment, as their cost of production is cheapened.

The cost of metallic nickel is high, owing to the comparative scarcity of nickel ores, their low nickel content, and the somewhat costly metallurgy of the extraction of the nickel from them. On the other hand, certain nickeliferous iron ores contain nickel in sufficient quantities to yield ultimately a low nickel steel of good quality, the value of which is enhanced by the presence of chromium, which almost invariably accompanies the nickel. Such ores exist in enormous deposits in various parts of the world, the most notable being in Cuba, Greece, Borneo and Celebes.

Another possible source of low nickel steel, which has not yet been exploited, is in the blast furnace slags resulting from the smelting in Ontario of the Sudbury nickel ores.

Of all known deposits of nickel ore these Sudbury deposits are by far the most important. At the end of 1916 it was stated that the ore which might ultimately be obtained from them would probably exceed 150 million tons, which would be sufficient to maintain the normal annual output for a century [1/p. xxix].

Other known deposits of nickel ore within the Empire are in Tasmania, South Africa, India and Egypt. So far as they have been explored, they appear to be comparatively small, and as sources of supply of nickel ore are not likely to be

seriously exploited so long as the large Sudbury deposits are available. Nevertheless, they constitute a useful mineral asset.

Of nickel deposits in foreign countries those of New Caledonia are second in importance in the world to those of Sudbury. Large quantities of ore have already been mined, and there is no doubt that considerable supplies of payable ore are still available.

For some years past Norway has produced appreciable quantities of nickel from native ores, but so far as is known the ore reserves are not large. A considerable tonnage of low-grade ore is mined in Germany, and it is reported that in Austria during the war old mines were reopened, and, although the ore available was also low-grade, a large quantity was mined.

NICKEL MINERALS

The nickel-bearing minerals are fairly numerous, but only a few of them are important. The following list includes the best known, and gives some of their properties :

Class of Mineral.	Name.	Formula.	Nickel Content %	Specific Gravity.	Hardness.
Sulphide .	Pentlandite	$(\text{FeNi})\text{S}$	18-40	4.60	3.5-4.0
" .	Polydymite	Ni_2S_3	59.4	4.54-4.81	4.5
" .	Müllerite	NiS	64.6	5.3-5.65	3.0-3.5
" .	Linnærite	$(\text{CoNi})_2\text{S}_4$	12-33	4.8-5.0	5.5
Arsenide .	Nickoite	NiAs	43.9	7.33-7.67	5.0-5.5
" .	Chloanthite	NiAs_2	28.1	6.4-6.6	5.6
Sulph - Arsenide .	Gersdorffite	NiAsS	35.4	5.6-6.2	5.0-5.5
Antimonide.	Breithauptite	NiSb	32.8	7.54	5.5
Sulph-Antimonide .	Ullmannite	NiSbS	27.8	6.2-6.7	5.0-5.5
Hydrated Silicate .	Garnierite	$\text{H}_2\text{NiMgSiO}_4 \cdot n\text{H}_2\text{O}$	15-33	2.3-2.8	2-3
Hydrated Arsenate .	Annabergite	$\text{Ni}_3\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$	29.5	3	1.5-2.0
Hydrated Carbonate	Zaratite	$\text{Ni}_3\text{Co}_2(\text{OH})_8 \cdot 4\text{H}_2\text{O}$	26	2.6-2.7	3.0-3.2

Nickeliferous pyrrhotite is usually regarded as an ore of nickel, but, strictly speaking, it is not a compound of nickel, or a nickel mineral, seeing that the metal occurs in the pyrrhotite as

mechanical inclusions in the form of pentlandite, polydymite, or possibly some other nickel sulphide mineral. There is, however, a possibility that part of the nickel may have replaced a part of the iron in the pyrrhotite.

Nickeliferous pyrite and marcasite not infrequently occur in the Sudbury deposits, and most probably the nickel replaces a part of the iron in those minerals there.

Pentlandite is the most common nickel mineral at Sudbury, where it is intimately associated with pyrrhotite and chalcopyrite. Its composition varies greatly as its iron and nickel contents are mutually replaceable.

Polydymite is also found in some of the Sudbury mines, but is not common.

Millerite is quite unimportant as a source of nickel and *Linnæite* is only found in a few localities.

Nicolite is the most common arsenide mineral of nickel, but although widely distributed is rarely found in large quantities. The German name for this mineral is *kupfernicksel*.

Chloanthite is a relatively unimportant mineral, but is of common occurrence at Cobalt, Ontario, and also in the similarly complex ores of Schneeberg and Joachimsthal in Europe.

Gersdorffite, *annabergite*, *zaraitite*, *ullmannite* and *breithauptite* are all comparatively rare minerals.

Only second in importance to pentlandite are the silicate minerals of nickel of which *garnierite* is typical. These minerals are of very uncertain composition; the nickel and magnesium contents are mutually replaceable, and the proportions may vary widely in different specimens.

The silicate minerals garnierite, noumeaite, genthite and others have been described as separate minerals, of which there appears to be some doubt. According to F. W. Clarke [4], "these silicates are rarely, if ever, found as definite mineral species, although they have been described as such."

The following table of analyses illustrates various compositions of silicate minerals, in which (1) and (2) represent specimens of Oregon silicates, and (3), (4) and (5) silicates from New Caledonia :

Analyses of Nickel Silicate Minerals

No.	1	2	3	4	5
Silica	44.73	40.55	48.25	38.35	50.15
Alumina	1.18	1.33	0.55	0.40	0.57
Ferric oxide				0.15	trace
Nickel oxide	25.57	29.66	14.60	32.52	10.20
Magnesia	10.56	21.70	16.40	10.61	17.43
Water at 100° C. . . .	8.87	7.00	10.95	6.44	11.28
Water at red heat	6.99		8.82	11.53	10.37

Native nickel approaching purity is not known, but small quantities of *native alloys* of nickel and iron of terrestrial origin have been found in New Zealand (*see* p. 43), Greenland, Oregon, California and British Columbia, while similar alloys are common constituents of meteorites.

DEPOSITS OF NICKEL ORE

The useful ores of nickel fall into three distinct classes, which differ in the character of their deposits and in their mode of origin, and follow in the order of their importance :

(1) *Sulphides*. Examples: Pentlandite, polydymite, linnaeite and millerite ;

(2) *Hydrosilicates*. Example: Garnierite.

(3) *Arsenides*. Examples: Niccolite and chloanthite.

The sulphide ores which accompany pyrrhotite and chalcopyrite are invariably associated with a norite type of rock. The ore-bodies are usually at, or near, the margin of laccoliths and are partly massive, consisting of metallic sulphides, and partly disseminated through the rock, but restricted to the marginal zone. The Sudbury nickel deposits are the best known example of the sulphide type. Here an enormous laccolith occupies the interior of a basin-like depression, and is overlaid with a considerable thickness of sedimentary and pyroclastic rocks.

Some geologists regard the nickel ores as being due to magmatic segregation, while others believe that they were introduced from solution along zones of crushing and faulting. The genesis of the Sudbury ores is discussed on p. 32.

The hydrosilicate nickel ores, as found in New Caledonia and some other parts of the world, occur in weathered and decomposed zones of the basic igneous rocks, known as peridotites, frequently altered to serpentine, in which the nickel is considered to have been a primary constituent. During the decomposition stage the nickel minerals appear to have been dissolved and deposited from solution in shrinkage cracks and seams, and also brecciated portions of the mother rock.

The arsenides of nickel are usually amongst the minor minerals of the so-called "silver-cobalt-nickel-arsenide" ores such as are found at Cobalt, Ontario. The mineralization of these ores is very complex, and in most cases is considered to have taken place in two or more stages.

The Cobalt occurrences are quite typical; the ores are found occupying narrow almost vertical veins cutting metamorphosed fragmental rocks of pre-Cambrian age, known as the Cobalt series. This series and the underlying Keewatin have been intruded by a huge mass of dolerite, which forms a sill. In this case the vein material contains barytes, fluor-spar, dolomite and quartz, all typical of minerals deposited from aqueous solution, and this fact leaves no room for doubt that the metallic minerals had a similar origin.

W. G. Miller [5] considers that the source of the mineralization was magmatic waters, which accompanied or followed the dolerite eruption.

Similarly mineralized veins of ore occur in various parts of the world, notably at Schneeberg in Saxony and Joachimsthal in Bohemia. They occur in rocks of widely varying character, which seems to show that the source of the nickel and associated metals in these veins must be sought not in the immediately enclosing rocks, but in a different and probably deep-seated zone.

MINING OF NICKEL ORES

Different nickel ore deposits necessarily involve different methods of mining, but the methods adopted at Sudbury, Ontario, and at New Caledonia are typical of those in use for mining the pyrrhotite and silicate ores respectively.

The principal Sudbury mine is the Creighton, and the mining practice in use here is a fair criterion of that employed on the field generally. The Sudbury nickel ore deposits and the enclosing metamorphosed rocks are mostly hard and compact, making the mining operations free from special difficulty. The Creighton ore-body has a maximum length of about 1,000 ft. and an average width of over 100 ft. It has been proved to a depth of about 2,000 ft. measured on the dip of the ore-body, and the ore reserves at the end of 1915 were calculated at 10 million tons. At that date the mine had yielded 4,611,000 tons of ore, of which 3 million tons had been obtained from open working. The mine was started by the removal of 10 ft. of overburden, and the exposed ore was then removed by quarry methods, being raised by means of cable derricks. As the depth of the workings increased an inclined shaft was sunk in the adjacent foot-wall country, roughly parallel to the dip of the ore-body, and crosscut connections were made to it from the opencut workings. This permitted of the ore being raised through the shaft. With further increase in the depth of the workings it became expedient to abandon open for underground workings.

The present system of mining, which has been employed in all work below the 6th level, consists in shrinkage stoping with alternate pillar and stope, the rib pillars being 15 ft. and the stopes 6 ft. in width. The shafts and main haulage ways are in the foot-wall country rock, the former being sunk more or less parallel with the dip of the deposit, and the latter driven at intervals of 120 ft. vertical, with drifts running north and south. The main haulage levels are connected by a series of rises. The crosscuts, which traverse the ore-body from foot-wall to hanging-wall, are turned off every 75 ft. on the centre-lines of the pillars, and box-holes are raised from the sides of the crosscuts on alternate sides every 15 ft. In each pillar there is a rise in ore along the foot-wall contact from level to level, which is used as a man-way, for ventilation purposes, and for the passage of tools. Where the deposit is very flat, intermediate levels are used; there may be as many as three of these between two main haulage levels (*i.e.* 30 ft. vertically one above the other). In stoping, headings 20 ft. wide are

first carried along each side of the stope at an elevation of 18 ft. above the floor of the crosscuts. These headings are connected across the stope and with the hanging-wall by ordinary stoping methods from one box-hole to the next. In the next stage the elevation of the stope along the foot-wall is raised, and a breast stope is carried towards the hanging-wall.

Back stoping progresses from foot-wall to hanging-wall, carrying a bench from 10 to 12 ft. high, a thickness of 25 ft. being left below the floor of the stope above. This support is removed by thinning and blasting through on the hanging-wall side, the entire floor being afterwards removed by retreating in stages towards the foot-wall [6/pp. 550-61].

The pillars are mainly recovered after the floors have been cut through, and when sufficient ore has been drawn off. Hauling stations are provided at certain levels to which all broken ore on intermediate levels is conveyed through passes. Large pieces of ore are retained on a grizzly and are passed through jaw crushers at the hauling stations before going to the loading bins for hoisting.

In New Caledonia, the superficial character and somewhat friable nature of the ore call for a distinctly different method of mining. The depth of workable ore is restricted to 25 or 30 ft. It is prospected by sinking pits, and a payable area is defined by a series of pits along and across it.

The ore is usually found on hill-sides, and should the preliminary work give satisfactory results, contour lines 25 ft. apart vertically are run along these and are graded and known as "levels." Tracks are then laid, and mining is commenced by removal of the overburden, if any. The ore is picked or barred down, and is carefully sorted, the payable portion being gathered into heaps and the waste trammed to a dump. This procedure is continued so long as the level yields payable ore. Occasionally it is necessary to drill and blast the harder portions of rock, large low-grade blocks being worked round and left standing. The ore is conveyed to a central hauling station from which it is taken, usually by aerial tram, to stock piles for loading into ships or, if too far away, to a convenient point whence it is conveyed by light railway to the shipping point. Practically the only mine equipment necessary consists of

picks, shovels, wheel-barrows, ore cars and rails, and materials and appliances for the occasional blasting of rock [1/pp. 254-5].

METALLURGY OF NICKEL

The ores of nickel, whatever their type, do not readily lend themselves to ordinary methods of concentration.

It has been stated that flotation methods have been partially successful with nickel ores, but these methods are not known to be used either at Sudbury, Ontario, or in New Caledonia. The usual metallurgical practice is first to smelt partially roasted ore directly in blast furnaces to obtain a matte of iron, copper and nickel, which practice, while costly, has the advantage of a high recovery of the nickel content, and also of collecting the greater portion of any precious metals the ore may contain. This is, therefore, both a concentrating method and a stage in the reduction of the nickel ore to metal. The second stage of nickel extraction starts with the treatment of the nickel-copper-iron matte, and is much more complicated.

The preliminary roasting of a nickel sulphide ore is usually open or heap roasting. The object sought is to remove a portion only of the sulphur content; sufficient sulphur must be left to combine with the nickel, the copper and some of the iron in the next operation, which consists of smelting the partially roasted material with due proportions of coke and flux in a blast furnace. The pyrrhotite in these ores is almost entirely converted to silicate of iron in the blast furnace, and the composition of the slag is from 30 to 40% iron (combined with silica), 0.3 to 0.4% nickel and 0.2% copper. Evidence was given to the Royal Ontario Commissioners to the effect that these slags might profitably yield a nickel-copper steel of good quality, more particularly if worked as an adjunct to the smelting of the nickel ore, rather than as an independent operation [1/pp. 56-60].

The normal annual production of this slag at Sudbury is upwards of $1\frac{1}{2}$ million tons, containing from 5,000 to 6,000 tons of nickel and about half that quantity of copper. This might be expected to yield about 500,000 tons of steel, containing approximately 1% nickel and 0.5% copper. The typical

matte obtained at Sudbury from the blast furnace contains 16 to 17% nickel; 7 to 8% copper; 45% iron; and 26% sulphur [1/p. 445].

The matte, while still molten, is taken to a converter in which a blast of air oxidizes the greater portion of the iron, so that with the fluxing material used, it forms a slag containing 3% nickel. This slag is added to a blast furnace charge. The matte now consists of a mixture of practically iron-free copper and nickel sulphides.

The treatment of enriched matte to produce refined nickel has hitherto been carried out by three principal methods known respectively as the Orford, the Mond and the Hybinette methods. Only the outlines of each process are given here. The methods differ widely from each other, and for full descriptions a modern work on metallurgy should be consulted.

Orford Process.—The matte is fused with a given quantity of sodium sulphide, the result of which is that the upper and more fusible layer will contain most of the copper and the iron, if any, and the bottom layer, nickel sulphide chiefly. The separation can be made practically complete by one or two repetitions of the fusion. The two products are tapped separately from the melting furnace. The nickel sulphide is washed, dried and roasted with salt. By this treatment it is converted into insoluble oxide, while the copper is converted into a soluble chloride and can be dissolved out.

The nickel oxide is reduced to a form of nickel suitable for marketing.

The process is said to yield nickel 99% pure, but is believed to result in the sacrifice of a large proportion of the precious metals. It is by a modification of this process that the valuable alloy of nickel and copper known as monel metal is produced (see p. 19).

Mond Process.—The Mond process is one of great ingenuity, and depends upon a series of remarkable chemical reactions. The bessemerized or converter matte is roasted down to about 2% sulphur. This treatment is followed by a leach with a 10% solution of sulphuric acid, by which about 70% of the copper content is dissolved out, but very little of the nickel. The solid residue, washed free of acid, is transferred

to the top of a "reduction" tower, in which it slowly descends, meeting in its passage an upward stream of water gas. This gas reacts on the nickel oxide at a temperature of about $350^{\circ}\text{C}.$, and reduces it to metallic nickel. The reduced material is then passed to another tower known as the "volatilizer," in which a temperature of 50° to $80^{\circ}\text{C}.$ is maintained, and it is here brought in contact with producer gas rich in carbon monoxide. The carbon monoxide reacts with the finely-divided metallic nickel to form a volatile compound called nickel carbonyl, $\text{Ni}(\text{CO})_4$, which passes out of the tower mixed with the producer gas. This mixture is led through "decomposing" towers, heated internally to $200^{\circ}\text{C}.$ At this temperature the nickel carbonyl dissociates into nickel and carbon monoxide. The nickel is collected by passing the heated gas, containing nickel particles in suspension, through a mass of nickel granules, on which the nickel deposits in concentric layers. The granules, which have reached a given size, are removed by screening and are marketed as such.

The process yields a very pure nickel; the whole of the precious metals in the matte is recovered and the copper finds a market as copper sulphate.

Hybinette Process.—The Hybinette or electrolytic nickel-refining process originated in Norway, and by this method the concentrated matte is roasted and extracted with acid as in the Mond process. The solid residue contains about 65% nickel, 3 to 8% copper and traces of iron, and is melted down and cast into anodes. Cathodes consisting of iron plates coated thinly with graphite are used, and an electrolyte, which is a solution of 45 grams of nickel sulphate per litre, practically free of copper.

The current employed is a direct one, and the voltage is 160 to 170. As electrolysis proceeds the electrolyte becomes enriched in copper and requires treatment for its removal. This consists of transferring the solution into other vats in which are placed broken pieces and the short ends of anodes, the nickel in which has a similar action in precipitating copper as metallic iron. At the same time the solution takes up nickel and is thus restored to its original nickel strength.

The nickel deposits on both sides of the cathode, and when

it has reached a thickness of $\frac{1}{8}$ in. it is stripped off in sheets which weigh about 20 to 30 lb. each. The nickel is about 99% pure, but a higher degree of purity can be reached if desired. The precious metals pass into the anode slimes, and are recovered. The copper is recovered partly as cement copper as mentioned above, and partly as electrolytic copper.

The process has been adopted by the British American Nickel Corporation [1/p. 476].

A Norwegian metallurgist named Gustavus Haglund claims that the use of insoluble, instead of soluble anodes, in this process is a considerable advantage [7].

G. A. Guess of Toronto University carried out some investigations in nickel refining for the Ontario Nickel Commission in 1916, and devised an electrolytic process in which a practically pure nickel sulphate electrolyte was used, a small amount of glue being added. Insoluble lead anodes were used, and the current density was 250 amps. per square foot [1/p. 479].

An improvement on this process since devised by Guess, is to add to an impure nickel sulphate electrolyte finely-divided calcium carbonate in suspension, and to enclose the cathode in a sack diaphragm. The action of the calcium carbonate is to form a double basic sulphate of copper and nickel which precipitates; it is said that the nickel produced is practically pure [8]. Of the many other nickel refining processes which have been proposed none appears to have come into commercial use.

PHYSICAL PROPERTIES OF NICKEL

Nickel is a white metal taking and retaining a brilliant polish. It possesses malleability and ductility in a high degree and, when pure, can be rolled into sheets 0.0008 in. thick and drawn into wire 0.0004 in. diameter. The specific gravity of cast nickel averages about 8.5, and that of rolled or hammered nickel about 8.7, but it depends upon the mechanical treatment the metal has received. The tenacity of nickel also varies with the mechanical and heat treatment it has received, but for wrought metal after annealing, the tensile strength is about 42 tons to the square inch. The melting point of nickel is 1,452° C.

Nickel is attracted by a magnet and becomes magnetic, its magnetic power as compared with that of iron being as 1 to 1.5. A magnetic transformation takes place at 340° C. to 360° C.; at higher temperatures nickel is non-magnetic. The electrical conductivity of nickel when pure is about 12.9 if that of silver be taken as 100.

CHEMICAL PROPERTIES OF NICKEL

Nickel is not readily oxidized or tarnished at ordinary temperatures, but acquires a coating of greyish-green oxide after prolonged exposure at a red heat.

Hydrochloric and sulphuric acids attack nickel very slowly, but nitric acid and aqua regia dissolve it readily. Fused alkalis do not seriously attack nickel, hence its employment for crucibles for conducting fusions in which sodium peroxide is used. Nickel forms numerous compounds with other elements, of which those most commonly encountered in the mining and metallurgy of the metal are the oxides, sulphides, arsenides, silicates, sulphate, chloride of nickel and nickel carbonyl.

USES OF NICKEL

One of the most largely used of the less common non-ferrous metals, nickel is employed mainly in the form of alloys with other metals, but also, to a much lesser extent, in the form of metal. The alloys of nickel are described below.

Owing to its non-corrosive properties nickel is used for cooking utensils, and for evaporating basins, crucibles and other small articles used in chemical laboratories and works. Larger pieces of apparatus are sometimes made of iron with a nickel lining, while a further quantity of metal is employed for electroplating articles of iron, steel, zinc, brass and many other alloys. Latterly it has been found possible to electroplate aluminium with nickel, which formerly could not be done. A large number of small articles of general utility are made of nickel, and several European and other countries employ unalloyed nickel for coinage.

Nickel is also used as an anode in storage batteries of the Edison type; in the production of malleable steel tubes; as wire and sheet for the construction of the electrodes in certain

wireless valves ; as a wire for making the points of sparking plugs ; as a gauze in the construction of atmospheric burners of the Mecker type and for furnaces ; and as one of the elements of thermo-electric pyrometers used for rough industrial purposes.

Comparatively new sources of solid edible fats, and also of some other fats suitable for the soap and candle making industries, are to be found in the form of " hardened " or hydrogenated oils. Under suitable conditions liquid oils, in the presence of hydrogen and certain catalytic agents, may be transformed into hard fats of various melting points, the hydrogen being absorbed by the unsaturated fatty acid constituent of the oils. Various substances act catalytically to accelerate this reaction, but of these only nickel and certain of its compounds appear to be sufficiently active for commercial use.

Nickel may be also employed as a catalyst in the enrichment of water-gas ; in the presence of nickel, and at 250° C., the carbon monoxide and hydrogen constituents interact to form methane and water, thus producing a gas of smaller volume, but with a much higher calorific value [9].

A further application of nickel as a catalyst, which may prove to be of considerable importance, is the result of a recent discovery that naphthalene and hydrogen in the presence of nickel can be converted into a series of compounds according to the number of hydrogen atoms which combine with the naphthalene molecule. When this number is four, the compound known as *tetralin* is formed. Tetralin is a colourless liquid of specific gravity 0.975. Its high boiling point makes it unsuitable by itself as a motor spirit, but mixtures of tetralin with benzol, alcohol or petrol are stated to be excellent motor spirits (*Petr. Times*, August 12, 1922).

The chemical compounds of nickel of industrial importance are not numerous. The oxide is used in the manufacture of glass, in the ceramic industry and for a few minor purposes ; the oxide and some other compounds are sometimes used as catalyzers ; nickel sulphate and the double sulphate of nickel and ammonium are largely used in nickel electroplating [1/p. 303].

COMPOSITION OF COMMERCIAL NICKEL

Commercial nickel is marketed in several forms: (a) As grains, cubes, rondelles or powder reduced from nickel oxide below the fusing point of nickel; (b) as concentric layers deposited, round a nucleus, from nickel carbonyl; (c) as cathode sheets resulting from electrolytic deposition; (d) in the form of blocks made by reducing nickel oxide above the melting point of nickel; (e) as malleable nickel, obtained as in (d) but with magnesium or some other deoxidizer added to it before being poured into ingots. The metal is prepared in the forms of rods, sheets, wire, etc.

Most of the nickel produced falls under class (d). The International Nickel Co. of Canada supply the following grades of nickel:

Description.	Nickel, %	Iron, %	Sulphur, %	Silicon, %	Carbon, %	Manganese, %	Copper, Arsenic, etc %
1. Malleable nickel rods							
" A "	99.00	0.55	0.025	0.10	0.15	0.15	—
2. Ditto " B "	98.75	0.50	0.025	0.20	0.15	1.75	—
3. Ditto " C "	96.75	0.75	0.030	0.20	0.15	1.75	—
4. Nickel Castings	98.95	0.50	0.035	—	0.16	—	—
5. Orford Electrolytic Nickel	99.84	—	0.005	—	0.025	—	0.03
6. Nickel Shot " A "	98.65	0.50	0.060	0.15	0.45	—	1.25
7. " " " X "	99.05	0.47	0.040	0.10	0.18	—	1.25

Malleable nickel is nickel from which dissolved nickel oxide has been removed by a deoxidizer, which is usually magnesium. Nickel cannot be rolled, forged or drawn without this preliminary deoxidizing treatment. Generally, shot metal is the form in which nickel is used in the nickel steel industry, and electrolytic nickel is the material used for producing high-grade "nickel silver" and for cupro-nickel alloys. Anodes for nickel electroplating may contain 88% and upwards of nickel. Impurities in the anodes facilitate the dissolution of the metal and the maintenance of the correct nickel concentration in the plating bath.

ALLOYS OF NICKEL

Nickel is used in alloy form with a number of other metals, but its chief use is in the production of *nickel steels*, the nickel

being added to steel to overcome the tendency to rupture under repeated alternating stresses, common with ordinary steels.

The term nickel steel covers extremely varied products of carbon, iron and nickel, and also products which may contain one or more additional metals.

Low Nickel Steels.—For general engineering and ordinary purposes simple nickel steels containing 3 to 4% nickel and low in carbon are the most important. These are usually produced by the open-hearth method, the nickel being added generally as metal at some stage of the smelting, or when the steel is in the molten condition. These low nickel steels alloyed with 0.5 to 0.8% manganese, possess high tensile strength and elastic limit as compared with the corresponding carbon steels, and are not less ductile. A nickel steel with 3.5% nickel and 0.38% carbon compared with a carbon steel with 0.2% carbon has twice the elastic limit, and an ultimate strength of 105,000 as against 60,000 lb. per sq. in. [3/p. 166].

Such nickel steels are usually employed for special purposes, including the manufacture of projectiles, guns, gun shells and armour plate; occasionally in bridge construction; in locomotive and other railway plant; for marine and stationary engines, electrical plant and turbines, and in the automobile industry.

Nickel-chromium Steels.—A most important range of steels is that which contains both nickel and chromium. The addition of chromium to steel in the presence of nickel, increases the strength, shock resistance and hardness. These steels are generally manufactured in three types, the compositions being approximately the following [1/p. 358]:

No.	Nickel. %	Chromium. %	Carbon. %
1	3.5	1.50	0.25 to 0.45
2	2.0	1.00	0.10 „ 0.45
3	1.5	0.50	0.10 „ 0.45

The first type is used chiefly for armour plate and armour-piercing projectiles. Under suitable heat-treatment steel of this type develops great strength combined with ductility.

Various samples have exhibited tensile strength ranging between 101,000 and 138,000 lb. per sq. in., the corresponding ranges of elastic limit being 77,500 and 119,000 lb. per sq. in.

The second type is used largely for automobile forgings. It gives high strength when properly heat-treated, has great hardness and good shock- and fatigue-resisting qualities [1/p. 358].

The third type is a largely used all-round engineering steel. It is used for automobile forgings and for a variety of miscellaneous drop forgings and machine parts. It carbonizes readily and is easily case hardened. It is more tractable in working, heat-treating and machining than the other types, and is also of lower tensile strength.

The chromium-nickel steels appear in many cases to be rapidly replacing the simple nickel steels [1/p. 406].

High Nickel Steels.—High nickel steels containing 20 to 50% nickel are not used on a large scale, but possess valuable properties. There is a large variety of these steels, but only a few of them are described here.

Invar is a nickel steel alloy containing about 36% nickel, 0.5% manganese and 0.5% carbon. It melts at 1,425° C., and can be forged, drawn and worked readily. It takes a fine polish, is highly resistant to corrosion, and is therefore employed for graduation scales. Its most remarkable property, however, is in its low coefficient of expansion of 0.0000008, which makes it particularly suitable for the construction of measuring and other philosophical instruments, and for chronometers and other clockwork [1/p. 399].

Platinite.—Another steel alloy of nickel is so called because it has the same heat expansion coefficient as platinum, for which it is used as a substitute for sealing into glass as the leading-in wires of electric incandescent lamps. Its composition is 54-55% iron, 46% nickel and 0.15% carbon.

Ferro-nickel is a term frequently applied to a nickel alloy, with 25% nickel, which is largely used in the construction of rheostats and as a general electrical resistance wire [1/p. 400].

Tico and *climax* are names given to nickel steels containing 28 and 24% nickel respectively. These are nearly incorrodible,

have high tensile strength, and retain their original elasticity after repeated heating. These properties, and their high electrical resistance, make them valuable resistance elements in electrical work [1/p. 401].

Nickel steels with 30% nickel are used for making marine boiler tubes. Their non-corrosive and other properties give a "life" to the tubes several times longer than when ordinary carbon steel is used [1/p. 402].

A steel containing : Nickel, 3% ; silicon, 1.5% ; manganese, 0.6 to 0.8% ; carbon, 0.5 to 0.6%, is said to possess the following mechanical properties : Tensile strength and yield point, 300,000 and 200,000 lb. per sq. inch respectively ; elongation, 10% ; reduction of area, 25% ; Brinell hardness, 550 [91].

Nickel-copper Steels.—Contrary to former ideas, investigations have now proved that copper may replace one third of the nickel in low nickel steels without detriment, thus permitting an economy in production. The proportion of copper that can thus be advantageously substituted appears to be limited [1/p. 417].

A series of physical tests carried out by G. A. Guess of Toronto University is of particular interest, as it suggested the possibility of the direct production of such steels from Sudbury nickel-copper ores, now being attempted on a commercial scale by a Canadian company, or from the ferruginous slags containing both nickel and copper obtained in the smelting of these ores [1/p. 414].

While the principal use made of nickel is for steel alloys there is a large number of non-ferrous nickel alloys, which serve many important purposes. A few of these are described below under different headings :

Binary Nickel Alloys.—The binary non-ferrous nickel alloys comprise three principal series : The *cupro-nickels*, the *manganese-nickels* and *chromium-nickels*.

The alloys of nickel with copper form simple solid solutions in all proportions, and, whatever these proportions may be, the resulting alloy possesses considerable strength and ductility, providing the casting conditions are correct.

Cupro-nickel is the name of a commercial alloy which con-

tains 80% copper and 20% nickel. It is one of the most ductile alloys known. This property makes it particularly suitable for deep stampings, and for press work such as motor-car radiators and lamps. It is of a beautiful silver-white colour and takes a brilliant polish. Its tensile strength depends upon the annealing conditions such as temperature and the time of treatment.

The higher the annealing temperature up to 750° C. the lower the tensile strength, but the ductility increases with the temperature of the operation [10/p. 80].

Monel Metal, a white alloy of nickel and copper, contains about 69% nickel and 29% copper, with small amounts of iron, manganese and silicon. It is produced by the International Nickel Co. of Canada from Sudbury nickel-copper matte without separation of the metals.

It melts at 1,350° C. ; it is about equal in weight to copper, but much harder, yet is extremely ductile. It can be easily soldered, brazed or welded.

It is produced in cast form or in bars, rods or sheets like iron or steel. Its tensile properties are of a high order, for, according to its mechanical and heat treatment, its breaking tension varies up to over 100,000 lb. per sq. in. [10/p. 80].

Monel metal also exhibits remarkable resistance to all classes of corrosion, including that of electrolysis, common with the poles and hanger rods used with high-tension electric lines. It is superior to bronze when cast for valves, liners and other parts of pumps, for acid conductors and containers in chemical plants and for refrigerating plants, where ammonia tends to cause great deterioration. When rolled it is specially suitable for pump and piston rods and for drawing into wire of all sizes down to 40 gauge.

Recently in the United States it has been coming into use for domestic utensils. It is a valuable material for the construction of turbine blades owing to its resistance to erosion by high temperature steam, and to the retention of a large proportion of its strength at high temperatures at which most metals and alloys would be dangerously weakened [10/p. 80].

Constantan, known also by other trade names, contains

60% copper and 40% nickel. While possessing high tensile strength, great ductility, resistance to corrosion and a handsome appearance, it is specially valuable in electrical work owing to its high resistance [10/p. 79]. It is used as an element in thermo-electric pyrometers.

Nickel-bronze, used for the so-called nickel coinage of about fifty countries or states, is an alloy of 75% nickel and 25% copper, and is excellent for the purpose both on account of its durability and its non-corrodibility. The quantity of nickel which otherwise enters into coinage is relatively small.

Nickel-manganese Alloys are less well-known and used than the cupro-nickels. They form solid solutions in all proportions, but so far their manufacture has been practically restricted to those containing 1 to 10% manganese. The most generally used alloy contains 3% manganese, and is used for sparking plugs and dental wire.

Nickel-chromium Alloys are amongst the most valuable of the binary non-ferrous nickel alloys, particularly those containing from 12 to 25% chromium. These retain their strength at high temperatures to a greater degree than any metals or alloys known, whether ferrous or non-ferrous. Even at temperatures of 1,000° C. they are said to form scarcely any scale, and possess remarkable toughness even after long and continuous exposure to such temperatures.

Lead-nickel Alloys.—Binary alloys consisting of small percentages of nickel in lead are stated largely to increase the resistance of lead to the action of both cold and hot sulphuric acid [10/p. 130].

One series has the following ranges of formulæ: Nickel, 10–20%; copper, 50–70%; zinc, 5–30%. Another: Nickel, 6–30%; copper, 40–60%; zinc, 14–30%. “Extra white” nickel silver has the formula: Nickel, 3%; copper, 50%; zinc, 20%. Sheffield nickel silver: Nickel, 24%; copper, 57%; zinc, 19%.

Nichrome, an important alloy, is composed of iron 26%, chromium 12% and nickel 60%. Its special uses are for incorporation into moulds for die-casting, for valves and valve seats for internal combustion engines, for crucibles, outer castings, annealing boxes and case-hardening or carburizing

boxes ; it is also of considerable utility for electrical resistance wires and electrical heaters, and also in pyrometer couples. It withstands continuous and intermittent heating up to 900°C . without corroding, pitting or oxidizing. It possesses considerable strength, is resistant to the action of sulphuric and some other acids and is therefore largely used in the construction of chemical plant.

Ternary Nickel Alloys.—The ternary alloys in which nickel is a constituent are numerous and include many of the so-called *nickel-silver* alloys whose properties are generally well known. They have a wide range of domestic uses and generally consist of copper, nickel and zinc, but the proportions vary widely. (See Imperial Institute monograph, *Copper Ores*, p. 29.)

Nickel-brasses.—Guillet in France has carried out some investigations as to the effect of nickel in low copper brasses, and has established the fact that alloys of high qualities result. These have ultimate strength up to 90,000 lb. per sq. in. with 20% elongation. In colour they vary from silver-white to golden-yellow, and are highly resistant to atmospheric corrosion [11].

Nickel-copper-aluminium Alloys contain about 90% copper, 5 to 7% nickel and 5% aluminium, and have valuable properties, including breaking strengths varying from 50,000 to 90,000 lb. per sq. in. [10/p. 129]. The properties of two such alloys are given in the following table :

Composition.			Treatment 15 minutes at 900°C . then :	Yield Point. Tons per sq. in.	Max. Load. Tons per sq. in.	Elongation. %	Reduction in Area. %
Copper. %	Nickel. %	Aluminium. %					
89·84	4·84	5·32	Quenched	7·6	24·22	87	72
			Air cooled	7·6	23·79	81	69
			Slowly cooled	9·4	35·58	70	60
87·48	7·31	5·21	Quenched	11·4	29·77	52	65
			Air cooled	11·6	27·06	64	70
			Slowly cooled	24·0	39·00	26	27

A ternary alloy of nickel 35%, copper 64%, and tin 1%, and other alloys somewhat similar in composition are practically stainless.

Other Nickel Alloys.—Nickel enters into the composition of certain alloys in which its function is not always particularly understood beyond the fact that its presence, sometimes in quite small proportions, has a decidedly beneficial influence.

Turbadium Bronze is an alloy containing approximately in percentages, copper 48, zinc 46.45, lead 5.1, tin 0.5, iron 1.0, aluminium 0.2, manganese 1.75 and nickel 2.0. It has a tensile strength of 35 to 42 tons per sq. in. and its elongation is from 14 to 20%. Its special use is for propeller castings, as, besides its great strength, it is almost incorrodible in sea water.

Illium is a complex alloy containing in percentages: Aluminium, 1; iron, 1; copper, 6.5; manganese, 1; nickel, 62.5; tungsten, 2; chromium, 21; and molybdenum, 5. Its special property is its high resistance to the action of acids [12].

Platinoid is an alloy of the nickel-silver type containing percentages: Copper, 60; zinc, 24; nickel, 14; and manganese, 1 to 2. It is used for electrical resistance wire [346].

English and American high-speed alloy steels do not usually contain nickel as a constituent, but a German high-speed steel is stated to contain 0.18% of this element [13/p. 31].

Nickel in small percentage enters into the composition of the valuable aluminium "Y" alloy developed at the National Physical Laboratory.

Malleable nickel is now being made in the United States for seamless tubes. A Welsh firm is experimenting with a process for the manufacture of nickel-coated sheets, with the object of substituting them for tin-plate. Electrolytic nickel of greatly improved mechanical properties has been produced by Chas. P. Madsen, and O. Bauer and E. Piwowsky have shown that 1% nickel in cast-iron increases its bending strength 30%, its compressive strength 30%, and its tensile strength 18% [52/1921, pp. 487-8].

PRICES OF NICKEL

Until lately, the price of nickel has varied very little in recent years, as will be seen by the following figures [14],

World's Production of Nickel Ore (Metal Content)
(Metric tons)

Country.	Material.	Approximate Nickel Content.	1913.	1914.	1915.	1916.	1917.	1918.	1919.	1920.	1921.
Canada ¹	Metal	%	22.533	20.646	30.880	37.475	38.262	41.973	20.211	27.829	8,754
Germany (Prussia) ²	Ore	2.00	271	251	335	1,661	2,972	1,871	583	—	321
Greece ³	"	0.50	87	68	103	51	8	60	5	—	—
Norway ⁴	"	1.03	690	794	892	808	379	33	200	422	—
Sweden ⁵	"	1.00	—	2	16	35	50	25	4	—	—
New Caledonia (Exports) ⁶	"	5.6	5,219	5,272	2,720	1,718	1,793	874	87	181	—
United States ¹	Matte	45.00	2,631	2,379	2,488	2,220	2,843	1,771	1,716	2,028	—
	Metal	—	219	384	746	833	365	400	464	331	100
World Production	—	—	31,670	29,796	38,180	44,801	45,772	47,007	23,270	39,791	—

¹ [31]. ² Calculated from figures given in *Mineral Industry*. ³ Calculated mainly from figures given in *Statistical Rept. Iron, Steel and Allied Tr. Fed., 1916*. ⁴ Calculated from figures given in *Min. Jour.* (November 12, 1921, *Cons. Rept.*).

which are the average London prices of the metal for the years 1917 to 1922, inclusive :

	1917.	1918.	1919.	1920.	1921.	1922.
Per long ton . . .	£200	£210	£200	£226	£195	£158

Since 1920, when the highest figure for the above five-year period was reached, there has been a more or less steady decline in the price of the metal. In July 1923 it was quoted as low as £135 per ton.

WORLD'S PRODUCTION OF NICKEL

No reliable statistics of the total world production of nickel metal can be obtained, as only in the case of Canada are official returns published of the amount of nickel in the ores mined and treated. But inasmuch as the Canadian production of nickel is considered to be 80 to 85% of this total, a close approximation to the correct amount may be estimated. The only large producer of nickel other than Canada is New Caledonia. During the war years transport difficulties and other circumstances connected with the war seriously reduced the New Caledonian output, but for the four years ending in 1914 an average annual output of 7,000 to 8,000 tons of nickel was obtained from about 100,000 tons of ore containing 5 to 6% nickel and about 5,000 tons of matte containing approximately 45% nickel.

World's Production of Nickel (Metal)

(Metric tons.)

Country of Refining.	1913.	1914.	1915.	1916.	1917.	1918.	1919.	1920.
England . . .	5,000	5,000	5,600	4,500	5,000	5,000	2,200	3,200
Germany . . .	5,200	4,200	900	400	1,300	1,000	1,000	1,000
France . . .	1,500	3,400	2,200	2,400	1,900	700	500	600
Norway . . .	700	800	900	800	400	100	—	100
Europe . . .	12,400	13,400	9,600	8,100	8,600	6,800	3,700	4,900
U.S.A. and Canada . . .	18,200	16,700	25,000	30,400	30,800	33,700	13,800	19,200
World Production . . .	30,600	30,100	34,600	38,500	39,400	40,500	17,500	24,100

In the table on p. 23 the world's production of nickel ore is given in terms of metal.

In the table on opposite page, taken from *Metallgesellschaft*, 1922, the world's production of nickel is arranged according to countries in which the metal is actually refined.

Metallgesellschaft estimates that the world's production of nickel in 1921 did not exceed 5,000 metric tons.

CHAPTER II

SOURCES OF SUPPLY OF NICKEL ORES

(a) BRITISH EMPIRE

EUROPE

GREAT BRITAIN

NICKEL ores are not found in Great Britain in quantities sufficient to make them of value, but a few occurrences are here noted.

In Cornwall, nickel and cobalt generally occur together, either in tin- or copper-bearing veins, associated with much ferruginous matter; or they occur in cross-courses near their intersection of such veins. They are rarely found except in combination with arsenic. The most important deposits have been met with at East Pool, Dolcoath, and other mines of the Camborne and Illogan district, and at St. Austell Consols and Fowey Consols, but very small quantities have been found in many other localities.

Borlase, in 1754, noted the occurrence of nickel at Peengreep, in Gwennap. In 1818, niccolite was raised at Pengelly mine, in St. Ewe district, but there is no record of the quantity mined. The ore occurred in a vein 7 in. wide, 150 ft. below the surface. From 1854 to 1861 nearly 134 tons of nickel and cobalt ores were obtained from St. Austell Consols, and about 13 tons of similar ore were raised from Fowey Consols and East Pool mines [15]. Pentlandite is stated to have been found in appreciable quantity at the Wheal Jane lead mine at Truro; in South Tresavean mine niccolite occurred with pitchblende, silver and lead ores; millerite was found at Wheal Sparnon; and at Roskrow United mines, near Ponsanooth, nickel was found with silver, copper and uranium ores and pyrite. At these mines granite is said to occur 420 ft. below the adit level [16].

Millerite has been reported in certain clay ironstones of the South Wales Coal Measures, notably those near Merthyr Tydfil.

Nickel minerals were found associated with iron ores at Moel Hiraddug, Cwm, in Flintshire. According to D. C. Davies [17/p. 309], the average nickel content was 2.3%.

In the early part of 1920 it was reported that C. S. Garnett had discovered a nickel mineral at Warren Carr, Darley Dale, Derbyshire. The nickel proved to be *zaratite* (a hydrated basic nickel carbonate), which forms a crust about half an inch thick upon decomposed dolerite surfaces in the mine workings. The purer portions of the mineral are of a pale emerald colour, but generally it is associated with *hydrozincite* by which it is masked [18], [19].

Nickel ores are also found in Scotland. From 1854 to 1867 *pentlandite* ore was mined at Coille-Bhraghaid, about 1½ miles S.W. of Inveraray, and similar ore occurs at Craignure, about 8 miles from Inveraray. The output of ore from the former locality appears to have been about 400 tons [20/p. 135].

Nickeliferous *pyrrhotite* carrying 1.7 to 3.0% nickel was discovered about 1885 on the west side of *Palnure Burn*, in *Kirkcudbrightshire*, at the base of a sill-like intrusion of *diorite* into *slate*. No attempt at serious mining appears to have been made on this deposit [20/pp. 127-8].

A collier in 1606 found a heavy piece of "red metal" in the burn at *Hilderstone*, *Linlithgowshire*, which afterwards proved to be native silver and *niccolite*. It was traced to a vein, which was afterwards opened up by several shafts. Native silver went down to a depth of 72 ft. and *niccolite* (non-argentiferous) to 180 ft. From 1870 to 1873 the mine was again worked, and the vein was found to be associated with a highly altered basalt dyke. A shaft was sunk to a depth of 225 ft.; limestone was met with at a depth of 93 ft., and was proved to be 54 ft. in thickness. In the limestone the vein carried *barytes*, *niccolite* and some argentiferous *galena*. It practically pinched out in the marl (volcanic ash) below the limestone. The mine was opened up again in 1896, and was worked on a small scale for *galena*, but was soon abandoned. The primary ores appear to be *galena* and *niccolite*. The secondary ores

are annabergite, erythrite (cobalt ochre) and native silver. The gangue is mainly barytes and calcite, the former of which contains small globules of albertite [20/pp. 61-2].

ASIA

INDIA

Nickeliferous pyrrhotite has been found amongst the copper ores of Khetri and other places in Rajputana.

Nickel in small quantities has also been detected in chalcopryite and pyrrhotite found associated with the gold quartz reefs of Kolar, and in pyrite said to be from the Henzada district of Burma.

Complex sulphide ores, containing both nickel and cobalt in quantities above mere traces, occur in the Tobala *taluk* in South Travancore. These ores consist of pyrrhotite, pyrite, chalcopryite and molybdenite. A surface sample assayed 1.20% copper, 0.64% nickel, and 0.08% cobalt with 12 grains gold and $2\frac{1}{2}$ dwt. silver per ton [21].

AFRICA

NYASALAND .

Nickeliferous pyrrhotite occurs in the Blantyre district of Nyasaland, where it is found in masses of norite. A sample examined at the Imperial Institute some years ago was found to contain pyrrhotite, chalcopryite and possibly pentlandite. It analysed 41.28% iron, 3.96% nickel, 0.28% cobalt and 0.99% copper, with a trace of platinum [22/p. 247].

UNION OF SOUTH AFRICA

Cape Province.

A deposit of nickeliferous pyrrhotite has been discovered in recent years at Insizwa, Cape Province. This occurrence resembles in most respects that at Sudbury, Ontario, and pyrrhotite deposits elsewhere. The ores occur chiefly at the contact of intrusive gabbro-norite with sedimentary rocks, which consist of sandstone, arenaceous sandstones and flaggy beds more or less calcareous. These sedimentary

beds are extensively metamorphosed as the result of the gabbro-norite intrusion both above and below the intrusive sheet, in the former case the strata being affected to a thickness of 400 ft., and in the latter to about 200 ft. as a rule. The extreme product of this metamorphism is a typical hornfels, and at the contact the signs of the original sedimentary character of the rocks have been destroyed almost entirely.

The intrusive sheet forms a rough oval about ten miles across, and from its periphery dips inwards, passing below an area of sediments, which thus lie in the interior of a basin-shaped mass of igneous rock. The strata, however, remains undisturbed and nearly horizontal, while the igneous material occupies a regularly curved surface of fracture. In this respect it differs from the Sudbury basin-like structure originating through subsidence below what is now the centre of the basin.

The most abundant ore mineral is pyrrhotite, and next in importance is chalcopyrite. Intimately associated with these is pentlandite, and bornite and niccolite have been identified. Appreciable quantities of platinum, said to be accompanied by palladium, are found in the ore.

Copper ore was discovered in the Insizwa area over thirty years ago in a small ravine known as the Waterfall Gorge. Analyses of samples from this place made by J. G. Rose in 1911 disclosed the fact that nickel, and also platinum, were constituents of these ores. This resulted in considerable exploration work being done, but only on a small scale. The average value of 14 samples of ore analysed by Rose showed about 4% each of copper and nickel, and 2 to 3 dwt. platinum per ton [23]. Particulars of the Insizwa deposit will be found in the Imperial Institute monograph, *The Platinum Metals* (pp. 19-20).

Owing to the infrequent exposures of the base of the gabbro, at which the ores occur, prospecting for ore necessitates driving, sinking or boring, and probably for this reason systematic exploration has not been extensive.

The ore was first opened up in a strip of light-coloured rock, about 200 ft. in length, and a few feet in width, enveloped in weathered gabbro and striking obliquely towards the contact. Immediately below this point a level has been driven for

distance of 600 ft. following the contact. A sheet of nearly solid sulphides (pyrrhotite and chalcopyrite) occurs for a considerable distance along the actual junction, with a maximum thickness of 2 ft. The hornfels is as a rule not mineralized more than 2 ft. from the contact, but above the contact the gabbro contains disseminated ore.

At another point the contact has been cut by an adit level, and here also the ore is fairly evenly disseminated through the gabbro for a considerable distance from the contact [24/p. 122].

The massive ore, so far as investigations go, rarely exceeds a foot in width, and the chief source of nickel is likely to be in the disseminated ore, the width of which is often considerable. This ore is said to carry about 7 or 8% sulphides, and to be self-fluxing [25].

Transvaal

Nickel has been discovered on the mine of the Rooiberg Co. at Blauwbank, Transvaal. Surface exposures are said to show ore containing 10% nickel for reasonable widths, but it is doubtful if any large quantity of ore of this grade could be obtained.

An occurrence of sulphide ore-bodies containing nickel and copper is reported at Vlakkfontein in the Rustenburg district, where the geology is said to resemble that of Sudbury.

A huge laccolith of red granite is surrounded by a marginal fringe of norite and basic rocks, the fringe being generally about 6 miles in width. The gossan outcrops on the marginal zone show signs of ancient workings, presumably for copper; no nickel is found in the first 40 ft. in depth, but below this point to the permanent water-level, about 100 ft. deep, nickel is found in percentages ranging from 0.57 to 3.25 and copper from 0.20 to 6.

The ore-bodies appear to consist of zones of varying widths, up to 58 ft., of pyroxene, impregnated with nickel-bearing pyrrhotite and chalcopyrite. The ore in one case contained gold to the amount of 9 dwt. per ton, and various analyses have recorded the presence of platinum metals.

A considerable amount of prospecting has been done, but

until the ore-bodies have been tested at greater depths, their value will be unknown [26].

In some recent investigations on the copper-nickel ores of the Rustenburg district, carried out by J. A. Ortlepp [27], samples of ore examined microscopically and chemically proved to be pyrrhotite, pentlandite, chalcopyrite, an unidentified mineral, *maucherite* (Ni_3As_2) and gangue (pyroxene group). Ortlepp concludes that the ore was formed by a process of magmatic differentiation, and that the order of separation of the minerals from the molten magma was as follows: Pyroxene (gangue), pentlandite, chalcopyrite, pyrrhotite. However, it must be borne in mind that the ore examined was not representative of the whole ore-body, hence the conclusions arrived at cannot justly be applied to the latter [27]. Certain tests made by Ortlepp indicated that the ore is not amenable to table, magnetic or ordinary flotation concentration, but that the concentration of the nickel into the form of matte is possible.

At Derde Gelid, Lydenburg, 200 miles to the east of Vlaktefontein, but geologically on the same horizon, copper and traces of nickel have been found in a prominent gossan outcrop. This outcrop lies within the norite-pyroxenite fringe at the end of the laccolite remote from Vlaktefontein, and should future developments at the latter place prove favourable, exploration work for nickel on this outcrop would be justified [26].

On the property of the Scotia Talc Mining Co. in the Barber-ton district, a nickel ore deposit occurs on the top of a range of hills immediately north of the railway between Joe's Luck Siding and the Sheba Bridge. According to T. G. Trevor [28], the geological formation is that of the Jamestown series of schists, and various openings have exposed a reef about 27 in. wide dipping conformably with the formation at about 60°S . The reef is highly stained with a green mineral, which has been identified as nickel silicate, and contains a high percentage of granular magnetite. The specific gravity of the ore is 4.5; a sample across the reef at about 3 ft. below the surface gave 17.2% nickel, and in the talc mine itself a sample of residual limonite, which results from a natural leaching of the talc, and is a marked feature of the deposit, showed 1.42% nickel.

An adit put in at the base of the hill has cut the reef in depth, and a drive has proved it for over 60 ft. The assay results of sampling at this depth confirm the surface indications.

A company, "The South African Nickel and Talc Mines Ltd.," has been formed to exploit the nickel ores and talc on the property [29].

Natal

In 1899, C. J. Gray [30] referred to the occurrence of nickel in the form of garnierite in a large body of serpentine in the Nkandhla district, Zululand, on the south bank of the Umhlatuzi River. Gray stated that nickel was widely distributed through the serpentine, but that at no point had he found it present in quantity.

NORTH AMERICA

CANADA

Ontario

In Canada, numerous deposits of nickel ore are known, but only the nickeliferous pyrrhotite deposits found in Ontario have been worked so far. The largest and richest known deposits of this type, and indeed in the world, are those of the Sudbury region, on the north side of Lake Huron, the geological formations of which are of pre-Cambrian age. The oldest rocks are known as the Grenville series, which consisted originally of sediments since metamorphosed to schists and gneisses. The group of rocks next above these is the Temiskaming or Sudbury series, which consists of quartzites, greywackes, arkoses, slates and conglomerates. This series is supposed to have a total thickness of 29,000 ft.; originally laid down in horizontal beds in the ocean, they have since been tilted into steeply inclined positions, and the greywackes and slates have in places been changed into schists and gneisses. The Upper Huronian or Aminikie series consists of sandstones, slates, tuffs and conglomerates, having an estimated thickness of 9,500 ft. This formation was deposited on a denuded surface

^f Lower Huronian and Laurentian rocks, and is therefore

younger than these. It occupies the depression known as the Sudbury basin. The most important group of rocks economically considered is the Keeweenaw, consisting at Sudbury entirely of igneous rocks: these contain the nickel-copper ore deposits. It was after the deposition of the above formations that the norite-micropegmatite sheet was injected. It spread itself out in the form of a laccolith between the Upper Huronian conglomerate and the older denuded surface on which the conglomerate was deposited.

It is estimated that this laccolith sheet extends over an area exceeding 500 sq. miles. Some geologists believe that it cooled slowly and became differentiated into three distinct layers, namely, a lowermost layer of rich nickeliferous pyrrhotite ore, a middle layer of norite containing some pyrrhotite, and an upper layer of micro-pegmatite, or fine-grained granite. After intrusion the floor of the laccolith sank somewhat, and the intrusion assumed the form of a basin to which the overlying sediments accommodated themselves. The basin is elongated, having a length of 36 miles and a width of about 16 miles, and the ore crops out along the edge of the basin [22/p. 233]. The ore which has been obtained so far has been taken from the southern or Sudbury side of the basin. The prevailing type of ore at Sudbury is the nickeliferous pyrrhotite which has been referred to as forming the lower edge of the norite-micro-pegmatite body.

The view most widely adopted to explain its origin is that it segregated gravitatively during the differentiation of the norite-micro-pegmatite magma, but there are geologists who consider that the ore was introduced by later infiltration of nickel-bearing solutions. The facts, as a whole, however, appear to favour the view of a gravitative magmatic segregation originally, which at certain points, where conditions have been favourable, has undergone modification of a secondary character by the action of aqueous solutions. Associated with the pyrrhotite is chalcopyrite, but the nickel appears to be present in the form of the mineral pentlandite scattered in grains of irregular shape and size through the pyrrhotite, from which it cannot be easily distinguished on a fractured surface. At the Vermilion mine, however, the nickel mineral in the

pyrrhotite is stated to be polydymite, which possesses a composition approximating to the formula Ni_4S_5 , but in which the nickel is more or less replaced by iron [3/p. 24]. It is suspected that polydymite, rather than pentlandite, may be the nickel mineral present in pyrrhotite in other parts of the Sudbury field, where it has not yet been proved. Other nickel minerals occasionally associated with pyrrhotite, are millerite, gersdorffite, niccolite, magnetite and tinstone. In certain veins that traverse the norite-micro-pegmatite sheet, the minerals blende, galena and molybdenite are found, but the origin of these is probably different in character from that of the nickel minerals occurring at the edge of the intrusive. The Sudbury nickel ores also include, gold, silver, platinum and palladium in small quantities, and an appreciable quantity of these is recovered in refining the nickel in the matte obtained by smelting these ores.

The platinum has been identified in some cases as *sperryllite*, an arsenide having the composition expressed by the formula PtAs_2 , and it is believed that this mineral disseminated in microscopic grains through the nickel-bearing ore is the source of the platinum obtained in the mattes from smelting the ores. Sperryllite appears to be present chiefly in the chalcopyrite, from which it can be separated by digesting the chalcopyrite with acid.

Where the ore deposits are exposed to the weather the sulphides become oxidized, their ultimate product being limonite, which is the typical gossan of the Sudbury region. This gossan, when found in large masses, indicates the probable existence of pyrrhotite in depth.

The ore-bearing zone of the intrusion shows a fairly gradual transition from practically pure sulphide minerals to material consisting mostly of silicates.

In shape the ore deposits are varied. Two main types are recognized :

(1) *Marginal deposits*, which occur at the basic margin of the norite, lying between it and the adjoining rock. These usually dip at moderate angles towards the middle of the basin. The length of these ore-bodies—from 100 to 700 ft.—is usually several times their thickness, which may vary from

a few feet to 100 ft. or more. Their depth is unknown, but in one case ore has been proved by diamond drilling to extend to 900 ft.

Sometimes the marginal deposits are modified by faulting and the ore is much crushed, and it is in these areas where the action of infiltration processes becomes apparent. Frequently the ore has been cut by later veins carrying copper and other minerals, such as blende and galena.

(2) *Offset deposits* are found which are connected with the basic edge of the norite intrusion by dyke-like projections, or they consist of more or less separate masses, of ore and norite having no visible connection with the main body of rock.

The offset deposits are of two types, one in which the ore-bodies are roughly cylindrical or columnar in shape and extend to great depths. Examples of these are provided by two pipe-like ore-bodies at the Victoria mine, one of which has been proved by sinking to a depth of 2,312 ft. Such bodies are richer in copper and precious metals than the ordinary marginal bodies, and usually contain quartz and carbonates.

The other type of offset is sheet-like and is more or less parallel to the basic edge of the intrusion, but at a considerable distance from it. The Foord-Stobie deposit is of this character. It is about a mile distant from the edge of the intrusion, and runs roughly parallel with it for a distance of over two miles. Drilling operations have proved its extension in depth to 1,000 ft. [3/pp. 35-8].

It is estimated that the ores, as mined, contain an average of 45% iron, 3.09% nickel and 2.12% copper. The 50% matte obtained by smelting the ore contains 0.02 to 0.30 oz. gold, 2½ to 7 oz. silver, and 0.17 to 0.5 oz. platinum per ton [3/p. 108].

The nickel deposits of the Sudbury region both in magnitude and richness in nickel contents reduce all other known deposits of nickel ore to comparative insignificance, and they are also by no means unfavourably situated for the distribution of their products to nickel refining and nickel using centres. A conservative estimate of the proved ore in 1916, obtained by the Ontario Nickel Commission, placed this at 70 million tons,

and the Commissioners, from information supplied them, regarded the probable and possible ore supply to exceed 80 million tons [1/p. xxix].

In 1918, 1,559,892 short tons of Sudbury nickel-copper ore were smelted, producing 87,184 tons of matte, the nickel and copper contents of which amounted to 48,886 and 23,482 tons, respectively. The refined nickel produced from the nickel-copper matte amounted to 1,082 tons. In addition, cobalt-nickel ores yielded 122 tons of refined nickel. The total Canadian nickel production from all sources amounted in that year to 46,254 tons [31].

The output of nickel ore from the Sudbury deposits, from the date production commenced (1887) until the end of 1921, amounts to 15,983,196 short tons, estimated to contain 437,831 tons of nickel and 254,102 tons of copper. The value of the above is approximately 181 million dollars.

For the year ending December 31, 1922, there were produced 17,324 short tons of Bessemer matte, the nickel and copper contents of which amounted to 8,667 and 5,421 tons, respectively. During the same period 71 tons of nickel were obtained from silver-cobalt ores, which are not included in the above.

Since the close of the war there has been a depression in nickel mining, mainly owing to the large accumulation of stocks of refined metal and matte, and early in 1921 the British American Nickel Corporation closed down mine, smelter and refinery, and was followed later by the International Nickel Co. of Canada. The Mond Nickel Co. alone operated throughout that year, but on a reduced scale. Operations were gradually resumed in 1922.

While the Sudbury deposits of Ontario are the only large nickel ore deposits in that province, several others are known. Of these, the only one which has been worked for ore is the Alexo mine in the township of Dundonald, near Matheson, and about 150 miles due north of Sudbury [1/p. 229], [32].

In its nature and mode of origin this deposit bears a close resemblance to those of Sudbury except that the matrix is a serpentine rock instead of norite. The serpentine is intrusive

in andesite-rhyolite and the ore deposit occurs at the margin of the intrusion. Mineralogically the ore agrees with the Sudbury ores. The deposit has a proved length of 700 ft. and width varying from 3 to 40 ft. It has been opened up to a considerable depth, and has been proved by drilling to a depth of 240 ft.

The ore occurs both as massive sulphides occupying spaces and cracks along the contact, and also as fine veinlets and in fractures in both walls, and disseminated in the serpentine.

These two types of ore are said to show a distinct contact, not merging one into the other, from which it has been suggested that the massive ore is a later formation. C. W. Knight considers the latter is "a final invasion by the last residual ore solutions from the deepest portion of the peridotite magma after its upper and outer portions were already solid, and which, by further cooling, shrank away from their surrounding walls in certain cases."

The massive ore, which consists for the most part of pyrrhotite and pentlandite, with traces of chalcopyrite and pyrite, carries 6 to 8% nickel, while the disseminated ore carries about 3%. It was the practice to mine and ship these together, giving a mixed product containing about 4½% nickel. This mixed ore, which is self-fluxing, was sent to the Mond Nickel Co.'s smelter. Up to the end of December, 1915, the developed ore in this mine was given at 60,000 tons above the 120 ft. level. The Alexo mine has produced altogether about 50,000 tons of good ore, but it is not now being worked.

The geology of this district is obscured by a heavy covering of drift, under which other nickel ore deposits may exist. That such may be the case is suggested by the fact that 1½ miles S.W. of the Alexo mine, and in the same township, serpentine masses are found in contact with andesites containing appreciable quantities of disseminated nickeliferous pyrrhotite, as at the Alexo mine. Although the geological associations are similar, no attempt had been made, up to a recent date, to test these deposits.

A discovery of nickel-copper ore which may prove to be of importance has recently been reported from Shebandowan Lake, about 70 miles west of Port Arthur on Lake Superior.

Cross, giving information later in his official report, states [33] that the deposit consists of pyrite and smaller quantities of pyrrhotite containing nickel as polydymite, and of copper as chalcopyrite with about 0.3% cobalt. The nickel and copper are present in about equal amounts, but in places there are great variations. Other minerals of nickel and cobalt, chiefly arsenides, have also been identified. The ore-bodies occur as lenses, and are connected by vein-like occurrences of ore. These lenses vary from 2 to 20 ft. in width, the length being proportional to the width. The massive ore carries 8 to 12% nickel. A sample submitted to the Geological Survey for examination was reported to contain 0.16 oz. per ton of platinum metals, principally palladium. The country rock of the district consists chiefly of the Keewatin formation, which is in contact with a granite outcrop. Near the ore deposit it is a dark-green basic schist dipping at a steep angle. Dykes of serpentine, granite and porphyry are found along this contact, with which the ore deposit appears to be associated. About a mile to the south is a large area of serpentine, with which, it has been suggested, the ore may be connected, as is the case with the ore of the Alexo mine.

Numerous other occurrences of nickeliferous pyrrhotite are known in Ontario, but they are small and not of high grade. The townships adjacent to the Sudbury nickel range have naturally been extensively prospected, and small low-grade outcrops of nickel ore have been found in a number of places, especially beyond the east and west boundaries of the known areas of norite. Near Nairn Centre, 8 or 10 miles south of Worthington, several small deposits occur upon which a little stripping work has been done, but without important results [3/p. 111].

Nickel occurs as a minor constituent of the complex silver-cobalt ores of the Cobalt district of Ontario under conditions differing widely from those found at Sudbury.

Here the nickel is found as the arsenides niccolite and chloanthite associated with numerous other minerals occupying narrow, practically vertical cracks and fissures in Lower Huronian rocks known as the Cobalt series. As a source of nickel, however, these ores are not of great significance, and

such nickel as is recovered from them is a by-product in the extraction of their silver contents. Particulars of these deposits will be found in the Imperial Institute monograph, *Silver Ores* (p. 44).

A number of similar, but smaller, deposits of ores of this character are known in Ontario and other provinces of Canada, but so far have not been proved to be important.

British Columbia

It has been reported, but not yet officially confirmed, that nickel in appreciable quantity has been recently proved as a constituent of the ores found in the mine of the Gabbro Copper Mines Ltd. on the Jordan River in the Victoria Mining Division, Vancouver Island. Copper minerals associated with pyrrhotite were found in a mineralized zone, entirely enclosed in gabbro, and a sample of the pyrrhotite, assayed at the laboratory of the Provincial Bureau of Mines, is stated to have yielded 5% nickel [34].

New Brunswick

A deposit of nickeliferous pyrrhotite occurs near St. Stephen, New Brunswick. The ore is found in a mass of gabbro intrusive in Lower Palæozoic slates. A sample from this locality containing pyrrhotite was found to analyse: Nickel, 1.72%; cobalt, 0.16%; and copper, 0.31%. Some attempts have been made in the past to mine this ore, but its grade is apparently too low for profitable working [35].

Manitoba

Sulphide ore-bodies, containing considerable quantities of nickel and copper, were discovered in 1917 in the Maskwa (Bear) River area, and in 1920 in the Oiseau (Bird) River area, 12 miles to the south. The principal ore mineral in both districts is pyrrhotite containing more or less pentlandite and chalcopyrite. Ilmenite and magnetite are also present in large quantity. In both districts, according to H. C. Cooke [89], the ore minerals are concentrated within a sill of gabbro near its original base. This rock was termed norite by W. S.

McCann [90] and R. J. Colony [36]. Elsewhere in the sills only an occasional grain of sulphide or magnetite may be found. In both districts the sill has been tilted on edge. The sulphides and oxides form irregularly shaped accumulations, or segregations, within the gabbro. The basal zone of the sill, containing a notable proportion of sulphide, is rarely over 100 ft. in thickness, and commonly less. Cooke is of opinion that the ordinary processes of gravitative differentiation have caused the primary concentration of the sulphides, as at Sudbury, but there are evidences of secondary concentration, indicating that the sulphides have been dissolved and redeposited by solutions or vapours, acting about the time of consolidation of the gabbro.

According to R. J. Colony [36] analyses of various samples taken over the mineralized area at Maskwa show the following ranges: Copper, 3.60 to 0.68%; nickel, 1.68 to 0.29%; platinum, 0.03 to 0.01 oz. per ton.

The two deposits being so near to each other suggests that the norite (gabbro) may be continuous between them, in which case further discoveries of nickel ore in the region are not improbable [37].

Quebec

Nickel ores occur in various parts of Quebec, some of which have been mined for nickel in past years.

In the township of Orford, millerite occurs associated with chrome garnet and pyroxene in a calcite vein. The deposit was worked formerly, but mining operations were abandoned in 1883.

At Calumet, Pontiac Co., a deposit of nickeliferous pyrrhotite occurs associated with a mass of diorite, which is intrusive in gneiss and crystalline limestones. An analysis of a sample showed 3.88% nickel and 0.32% cobalt. The ore band is described as having a thickness of about 12 ft. At the Cowen mine, a shaft was sunk to a depth of 40 ft. on this deposit.

Refined metallic nickel has been recovered in Canada since 1915, but, previous to 1918, only in small quantities and as a

by-product in the smelting and refining of the silver-cobalt-nickel ores of Sudbury, Ontario. Nearly the whole of the nickel produced in Canada was, until 1918, exported in the form of nickel-copper matte to the United States and the United Kingdom, in which countries it was refined. In July, 1918, the refinery at Port Colborne, Ontario, of the International Nickel Company of Canada, Ltd., started operations. These works are said to possess a capacity of 7,000 tons of refined nickel per annum, but so far the largest production of any year has been 5,063 tons in 1919. The British America Nickel Corporation's refinery at Deschenes, Quebec, was completed in 1919, and was in operation in 1920. The capacity of the plant is given as from 7,000 to 8,000 tons of refined nickel per annum, so that the combined output of the two plants should henceforth account for the greater proportion of the Sudbury ores, with the exception of that refined in Great Britain by the Mond process.

The following table shows the quantities of nickel in the form of nickel ore, matte, speiss, and, excepting the year 1914, of refined nickel which were exported in the years 1914 to 1922 inclusive :

Canadian Exports of Nickel ¹

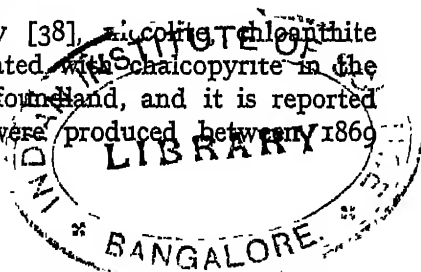
(Short tons)

Importing Country.	1914.	1915.	1916.	1917.	1918.	1919.	1920.	1921.	1922.
Great Britain .	3,239	5,420	5,805	6,200	4,941	6,172	3,122	5,620	2,768
United States .	21,995	17,197	29,416	35,110	36,583	32,810	18,691	16,861	1,446
Other Countries .	56	89	—	—	—	600	257	1,028	1,238
Total .	25,290	22,706	35,221	41,310	41,524	39,582	22,070	23,509	5,452

¹ *Annual Reports of the Trade of Canada* for the years 1914-20; *Monthly Report of the Trade of Canada*, March 1922, for the years 1921-22. The fiscal year ends on March 31.

NEWFOUNDLAND

According to J. P. Howley [38], ~~zincite, chalcophanite and millerite are found associated with chalcopyrite in the Tilt Cove copper ores of Newfoundland, and it is reported that 320 tons of nickel ore were produced between 1869 and 1876.~~



AUSTRALASIA

AUSTRALIA

New South Wales

Discoveries of nickel minerals in small quantities have, from time to time, been reported from various parts of New South Wales, but the only deposit of ore which appears to possess any value is that of a nickeliferous asbolite or earthy cobalt found at Port Macquarie. The geological formations at this point suggest that sedimentary rocks have been intruded by basic igneous rocks, which have since been altered to serpentine. The sediments have also been metamorphosed more or less, and now consist of an altered fine-grained sandstone. In the superficial zone the serpentine has been decomposed by weathering into a ferruginous earth. The most promising ore-bodies are found in this material in an irregular manner as nests and pockets of ore, in some instances associated with chrome iron ore composed of small grains of chromite loosely cemented together, but not in commercial quantities. Some years ago a small amount of cobalt and nickel ore was obtained from this deposit, but no production has been recorded since 1904 [39].

The following table of analyses show the percentage composition of (1) an average sample of ore and of (2) a picked sample of ore :

	(1)	(2)
Silica	8.06	6.40
Alumina	18.95	9.97
Ferric oxide	14.78	16.85
Manganese dioxide	31.05	36.50
Cobalt oxide	7.48	7.03
Nickel oxide	1.36	2.39
Lime Magnesia, etc.	0.16	2.51
Chromic oxide	0.41	0.40
Moisture and combined water	17.19	17.62
	99.44	99.67

Tasmania

Nickeliferous pyrrhotite occurs in small deposits in the North Dundas district near Zeehan. The ore is rich, but so far only comparatively small ore-bodies have been proved, the longest chute not exceeding 150 ft. in length with a width of 4 or 5 ft.; nevertheless, in one instance at least, a few thousand tons of ore have been mined and shipped. A typical lot of 100 tons of ore when assayed gave the following percentages: Silica, 5.24; iron, 32.80; sulphur, 32.66; nickel, 9.61; copper, 4.70 [40]. The ore also contains small quantities of platinum and silver [41].

The deposits occur in slate near its contact with serpentine, and also along the actual contact as solid ore. No disseminated ore has been observed in the serpentine near the contact. While it is not anticipated that any very large quantity of nickel ore exists in these deposits, the high nickel and copper contents are encouraging for further exploration.

Garnierite veins and nickeliferous serpentine occur near Trial Bay on the West Coast, which however have not been well explored. The serpentine forms a hill into which adit levels have been driven at three different points. One of these has intersected a 12 in. vein of high-grade garnierite ore assaying 13.35% nickel. The serpentine is said to carry about 0.5% nickel in the form of niccolite (NiAs), and as the ore is amenable to water concentration the profitable working of some portions of the hill is believed to be practicable [40].

Other occurrences of nickel ore in Tasmania, but apparently of no economic importance, are described by Twelvetees and Ward [42].

NEW ZEALAND

On the west coast of the South Island of New Zealand, an occurrence of a native nickel-iron alloy was discovered by W. Skey in 1885, and has been described by Ulrich [43].

The region consists of gneisses, mica-schists and chlorite-schists, which are broken through by vast stocks of an olivine rock of the composition of saxonite (olivine and enstatite) in part transformed to serpentine. The alloy was found in loose grains in the gravels derived from these serpentine and

saxonite rocks. It also occurs dispersed in minute grains in the serpentine. The mineral is known as awaruite (FeNi_2) and its percentage composition, according to Skey, is as follows: Nickel, 67.63; cobalt, 0.70; iron, 31.02; sulphur, 0.22; silica, 0.43.

(A similar mineral, josephinite (FeNi_5), has been found in detritus in areas of serpentine in S.W. Oregon and a few other localities in the United States [44].

While these minerals do not appear to be present in notable quantities they are interesting as being rare examples of a natural alloy of nickel and iron of terrestrial origin. Similar alloys, however, are common constituents of meteorites.

CHAPTER III

SOURCES OF SUPPLY OF NICKEL ORES (*continued*)

(b) FOREIGN COUNTRIES

EUROPE

AUSTRIA

DURING the European war, working was resumed in the old nickel-cobalt-copper mines on the Nöckelberg, near Leogang, in the Salzburg Alps region of Austria. The mines were abandoned near the end of the last century for lack of capital, but are reported to still contain large quantities of mixed ores of copper, nickel and cobalt, and a recent report states that these mines are now worked on a larger scale than any others of their kind in Europe [45]. Detailed information as to the present position of the mines is lacking, but the nickel output is probably quite small.

At Mitterberg, in the Salzburg Alps, deposits occur in Silurian clay-slates in the form of steep-bedded lodes 3 to 9 ft. in width, which are made up of sericite rock and quartz, the chief metallic minerals being those of copper and iron, with which nickel minerals in small quantity are associated [46/p. 439].

The primary ore is chalcopyrite, which, where the lode-filling has suffered no subsequent alteration, occurs in quartziferous siderite or ankerite with a varied pyrite content. Chloanthite, erythrite, arsenopyrite and some mercurial tetrahedrite, which readily decomposes with the formation of cinnabar, occur subordinately [47/p. 905].

The Leo lode near Salzburg, which contains pockets and nests of niccolite, smaltite and numerous other minerals, occurs in a Silurian dolomite [47/p. 949].

In the neighbouring Kitzbühel district, in the Tyrol, there are also bedded lodes in clay-slates (Silurian), which carry chalcopyrite with subordinate amounts of nickel, cobalt and other ores. The lodes on the Schattberg, in the Kupferplatte, sometimes contain tetrahedrite and millerite. On the Kelchalpe, the lode-filling consists principally of ankerite, quartz and *Falkenschiefer* (clay-slates with quartz flakes parallel to the cleavage) as gangue, and pyrite, niccolite, chloanthite, blende and galena, as the valuable minerals. Mining at Kitzbühel, now no longer of any importance, dates back to the eighteenth century [47/p. 907], [48].

CZECHOSLOVAKIA

Small quantities of nickel and cobalt ores are included in the complex mineralization of the well-known Joachimsthal district in Bohemia, but the output of these metals has never been important [46/p. 436].

An unconfirmed report of a nickel ore discovery at Schluckenau in Northern Bohemia appeared in the Austrian press during the war, which stated that the discovery consisted of a metalliferous vein about 8 ft. wide carrying 8.8% nickel.

At Dobschau (Dobsina) in the Liptau Mts., formerly in Hungary, Palæozoic slates are intruded by a diorite sheet, which has been altered at the contact to a chloritic schist rich in epidote. The mineralized veins cut the diorite close to its junction with the chloritic schists. These dip steeply, dividing into fan-like stringers in the upper part, but tend to disappear or grow barren at about 500 to 600 ft. in depth. The greatest width does not exceed 10 ft. and the vein-filling consists chiefly of siderite, calcite, ankerite, quartz and fragments of country rock.

The common ore is a mixture of smaltite and chloanthite, irregularly scattered through the veins in pockets, parallel layers or large compact masses. Chalcopyrite and bornite are occasionally observed. The richer ores yield 4 to 10% cobalt and 17 to 22% nickel.

This deposit was formerly actively worked, and from 1840 to 1880, 26,000 tons of ore mined yielded 1,000 tons of nickel

and a little cobalt. There appears to have been no recent production of nickel and cobalt ore from this deposit [49/pp. 340-1].

FRANCE

Many years ago, rich silver ore, associated with nickel and cobalt minerals, was discovered and worked at Chalanches, Dauphiné, France.

In the earlier period of working the silver only was recovered from these ores, and the nickel and cobalt speiss formed in the smelting operations was rejected with the slags and was used to fill swamps and to form road beds. In later times these slags were furrowed and turned over to recover their valuable contents, which were sold in England and Germany. More recently an attempt to manufacture cobalt pigments from the deposits was unsuccessful [50].

According to W. J. Henwood [51], the country rock is granitic gneiss; T. A. Rickard [50] describes it as consisting of crystalline schists. Several lodes have been worked here; their average strike is about W. 33° N., dip from about 50° to 70°, and average thickness less than 12 in. The ores consist of native silver, argentite, stephanite and ruby silver, with cerargyrite here and there. The silver ores are associated with smaltite, niccolite and annabergite, which minerals also occur scattered through the ordinary gangue. Asbolite (earthy cobalt), and erythrite (cobalt bloom) also occur, as well as various ores of antimony, lead and copper in small amounts. The gangue consists of quartz, calcite and altered country rock.

The mines were worked with difficulty on account of the high altitude (about 7,000 ft.) in which they are situated.

No nickel deposits of importance are known in France at the present time, but a large proportion of the New Caledonian output of nickel ore and matte is treated or refined there.

The total importations of nickel from all sources in France for recent years are given in metric tons as follow [52]:

	1916.	1917.	1918.	1919.	1920.	1921.
Dressed ore . . .	8,915	5,152	3,289	10,350	715	Nil
Metal . . .	1,760	1,871	823	1,059	114	214

The following are productions in France of refined nickel from imported ore and matte [52]:

	1916.	1917.	1918	1919.	1920.	1921.
Metric tons . . .	2,400	1,918	713	500	1,100	—

GERMANY

There are a few nickel deposits in Germany, but none is of great importance.

Deposits of nickel-silicate or garnierite occur near Frankenstein in Silesia in the Gläsendorf-Kosemitz Range. They are confined to four serpentine hills, which are surrounded by gneiss, blue-grey graphitic quartzite schists with white and red quartz bands, and coarse-grained syenite. The serpentine contains 41 to 42.5% silica, 36 to 42% magnesia, 0.25% chromic acid, and a small amount of nickel, said to be 0.34%. It is traversed by a system of N.N.W. quartz veins, and at the surface as well as along these veins the serpentine is highly altered to red earth, etc. "Green ore" consists of masses of red earth or highly decomposed serpentine traversed by veins of nickel silicate. When the metasomatic replacement of the rock is still more advanced "green knotted ore" arises, the brown-green variety of which constitutes the rich ore of the occurrence. The term "grey ore" is applied to a serpentine containing 1 to 2% nickel, which, though undergoing decomposition, still retains very clearly the character of serpentine. The green nickel ores represent hydrated nickel-magnesium silicates of very varied composition. The following minerals have been identified: Pimetite with 2.78 to 32.66% nickel oxide (NiO); schuchardtite, with 5.16 to 5.78% nickel oxide; and garnierite (?) with 38.61% nickel oxide. These garnierite occurrences have been formed by immediate lateral secretion and probably by processes similar to those which were active in New Caledonia, that is by decomposition proceeding from the surface and from quartz veins [47/pp. 958-62].

In 1901, 114 tons of nickel were obtained from 9,500 tons of ore. In recent years the annual output has amounted to from 10,000-12,000 tons of low-grade ore, such ore being smelted with high-grade ore from New Caledonia.

A deposit of nickel ore exists at Aeussert, Sohland, north of Schluckenau. A dyke of dolerite, rich in hornblende, 33 ft. in width, traverses the Lusatian granite in a W.N.W. direction, and along the northern border this dyke has been found ore-bearing for a distance of over 700 yd. The ore consists of nickeliferous pyrrhotite with some chalcopyrite and pyrite. It is sometimes massive up to several feet in width, but in other places it exists as impregnations in the dolerite. Specimens of the ore have yielded 5% nickel and 2% copper [49/p. 42]. According to *Deutsche Bergwerks* (April, 1918), the mining of this deposit, which was abandoned in 1904, had been resumed. The once famous cobalt deposits of Schneeberg and Annaberg in Saxony have also yielded small quantities of nickel [49/p. 344].

Nickel ore deposits have been reported to occur at Steben and Lichtenberg in Bavaria; Horbach in the Black Forest; and N.E. of Dillenburg in Nassau, but none of these occurrences appears to be important.

Germany's annual pre-war production of nickel ranged from 3,000 to 3,750 tons. In the German press it was stated that mining was actively pursued during the war, and that the output of ore was largely increased, chiefly from the Frankenstein mines. Recent productions of ore were [53]:

	1916.	1917.	1918.	1919	1920.
Metric tons . . .	83,046	103,619	93,555	29,151	16,050

Production of refined nickel in Germany has depended chiefly on imported ore and matte. No recent figures, with the exception of those of 1920, regarding these importations are available, but for the four years ending 1913 the imports of nickel-cobalt ore and also of metallic nickel in metric tons were stated to be as follow [52]:

	1910.	1911.	1912.	1913.	1920.	1921.	1922.
Nickel-cobalt ore.	9,937	14,897	14,987	13,658	3,067	—	311
Metallic nickel . .	4,606	2,598	2,027	3,315	886	2,148	2,724

The exports of metallic nickel in the same period were as follow [52]:

	1910	1911.	1912.	1913.	1920.	1921.	1922.
Metric tons . . .	1,381	1,592	1,677	1,673	56	202	265

GREECE

Both garnierite nickel ores and chromiferous iron ore containing some nickel are mined in Greece.

The latter occurs in the western part of Greece in the districts of Locris and Bœotia, and on the islands of Eubœa, Skyros and others of the Greek Archipelago. The most important deposits are in the district bounded by the bed of the drained Lake Copias and the west shore of the Talanta Channel. They are all within a few miles of the coast, the indentations of which furnish many convenient loading ports.

The composition of the ore after drying, varies within the following limits: Iron, 46-52%; alumina, 6-14%; silica, 5-11%; chromium, 2-3%; nickel and cobalt, 0.10-1.2% [54].

The production of pig iron and the ultimate product, chromium-nickel steel, from such ores has only become a commercial success in recent years. Formerly these ores presented a metallurgical difficulty in smelting, which has now been overcome, and a good grade chromium-nickel steel is produced from them in considerable quantities. Up to the end of 1913, about 2 million tons of ore had been mined, of which a large proportion was shipped to Great Britain. Further particulars of production will be found in the Imperial Institute monograph, *Chromium Ore*.

Closely associated with the chromiferous iron ores of Thebes and Locris is garnierite, discovered in 1909 to be irregularly distributed in serpentine on the foot-wall of the chromiferous iron deposits. This ore exists in nests or in small stringers, in a finely divided condition. Up to 1912, about 24,000 tons of ore containing 4 to 5½% nickel (after drying) had been mined and exported. No estimate of the quantity of this ore remaining appears to have been published, and presumably it is only accessible as the larger body of iron ore is mined. The composition of this garnierite ore may be judged from the analysis of a shipment of 2,000 tons to Norway in 1913, where it was mixed and smelted with the local pyrrhotite ore. The percentages of the various constituents are given as follow: Silica, 37; alumina, 9.81; ferric oxide, 28.37; manganese

oxide, 2.85 ; lime, 0.39 ; magnesia, 1.91 ; copper oxide, 0.07 ; nickel oxide, 9.17 ; chromic oxide, 1.37 [3/pp. 117-8].

The character of these Greek deposits of iron and nickel ores in many respects resembles those of the Cuban and New Caledonian deposits, which possess a similar composition, although the Greek occurrences show some important differences.

In the Locris and Boeotia districts, the ores occur as segregations of irregular character, and also in lenticular bodies either as fissures in limestone of Cretaceous age as at the mines of Thebes and Locris, or as contact deposits between the serpentine and limestone as at Tsouka, Karditza, Lutzi, and probably Pavlora. Moreover, the Grecian ores extend to a much greater depth than those of Cuba and New Caledonia.

ITALY

The nickel ore deposits of Italy are small and relatively of little importance, but, nevertheless, they have yielded ore on a commercial scale in past years. They are situated at Varallo in Piedmont in the Lake Maggiore district. The gneisses and mica-schists of this region are traversed by an intrusive mass of norite about $12\frac{1}{2}$ miles long and $2\frac{1}{2}$ miles broad, largely altered by regional metamorphism into a hornblende rock. Large masses of magnetite found at the gneiss-gabbro contact were discovered to contain 4 to 5% nickel and cobalt ; pyrite and chalcopyrite were also present, but the ore treated in the local smelting furnaces is said to have contained 1.2 to 1.5% nickel and cobalt [49/p. 39].

An appreciable quantity of nickel is imported into Italy. According to statements published in *Statistica del Commercio Speciale*, the quantities imported for the five years ending 1921 have been as follow :

	1917.	1918.	1919.	1920.	1921.
Metric tons . . .	3,293	3,215	2,136	452	286

The exports of nickel alloys and manufactures for recent years were as follow :

	1917.	1918.	1919.	1920.	1921.
Metric tons . . .	5	$\frac{1}{4}$	671	1,520	352

In 1916 the production of nickel steel is given as 4,210 tons, and of nickel-chrome steel, 5,964 tons.

NORWAY

There are about 40 deposits of nickel ore known in Norway, scattered over different parts of the country, mostly occurring in Archæan schists, but always accompanying areas of norite, or of a gabbro, too much weathered to enable its original constitution to be determined.

These ore deposits are comparatively small, the larger ones not exceeding 650 ft. in length with varying widths up to a maximum of 50 ft., but averaging about 10 ft. [3/p. 116].

The ore is only of moderate grade, averaging 1.5 to 2.5% nickel with about equal proportions of copper and small quantities of the precious metals. In mineralogical character, the nickel ore deposits of Norway resemble those of Sudbury, Ontario, consisting essentially of pyrrhotite, pentlandite and chalcopyrite, together with more or less pyrite and other minerals in association with norite.

With most of the deposits, the ore occurs at the periphery of the eruptive masses (gabbro or norite) in the crystalline schists [47/p. 294].

Nickel pyrrhotite deposits are found in the same region as the intrusive pyrite deposit of Skorovas, N.E. of Trondhjem. The Lillebjeldklumpen mine, near Tunsjö Lake, has a deposit of this type which contains about 3% nickel, with much copper and traces of platinum [55].

The richest nickel mine in Norway is the Flaad mine in Sättersdal, sometimes called the Evje mine on account of its proximity to the village of Evje, where smelting works have been erected. The ore at this mine occurs in a mass of uralite-gabbro, about 30 sq. miles in area. The depth of the mine is about 300 ft., but ore is known to exist below that depth. Up to 1908, this mine is said to have yielded about 75,000 tons of ore, equivalent to 1,350 tons of nickel and 800 tons of copper. The hand-picked ore usually yields 1.4 to 1.7% nickel, though, exceptionally, the yield may be as much as 2 to 2.5% [47/p. 297]. In 1913, the mine produced 28,500

tons of ore, and the Faso mine, near Haugesund, 2,000 tons, which, with 2,000 tons of nickel ore from Greece, was smelted at Evje, producing matte containing over 400 tons of nickel and 250 tons of copper.

Another mine near Ringerike, the Ertch mine, produced in the same year 13,000 tons of ore, which was smelted with 1,250 tons of imported ore, yielding together matte containing 200 tons of nickel and over 100 tons of copper [1/p. 265].

The matte from the Norwegian smelters is shipped to Kristiansund and refined by the Hybinette Electrolytic process of which a brief description is given in the section dealing with the extraction of nickel from its ores (*see* p. 11). The principal part of the output of Norwegian nickel prior to, and during, the war was sent to Germany and Austria under long-period contracts.

The Norwegian production of nickel is not large enough appreciably to affect the market for the metal, nor does it seem probable that Norway's nickel ore resources are either large enough or sufficiently rich in nickel to have that effect in the future. On the other hand Norway has the advantage of large potentialities for producing cheap hydro-electrical power, and this fact is not unlikely to make it economical to refine nickel in that country electrolytically from ores and mattes produced elsewhere.

The mines were closed down early in 1921. In 1920 and 1921 the exports of nickel from Norway were 53 and 273 metric tons, respectively [52/1921, p. 484].

RUSSIA

A deposit of nickel ore of the garnierite type occurs at Revdinsk in the Urals, S.W. of Ekaterinburg in a serpentine rock, samples of which have contained 4.8 to 1.92% nickel, but the ore generally is of low grade. The Revdinsk smelting works have been reported as producing 600 tons of nickel matte per annum within recent years, but this report lacks confirmation [56].

According to Turner [57], the nickel deposits of the Urals occur in Devonian schists and their associated igneous rocks.

In the Nijni-Karkadinsk limonite mine serpentine was met with in one of the shafts carrying a green mineral, which proved to be a silicate of nickel. Samples from 4 bore-holes assayed 0.72 to 3.24% nickel. Turner in 1910, found, at the bottom of shaft 12, a black dirt, which proved to be largely carbonaceous, carrying nickeliferous pyrite. The carbonaceous matter contained 1.69% nickel and cobalt, and doubtless represents a bed of coal or lignite much broken up by later serpentine intrusions. He considers the serpentine to be the mother rock of the nickeliferous-pyrite, which was brought from the serpentine in magmatic and other solutions. These solutions soaked into the adjoining siderite deposits and into the lignite bed, there depositing their mineral contents.

About 400 yd. to the N.W. of the Nijni-Karkadinsk mine, 100 pits have been sunk in clay containing green nickel ore, the area being 250 by 70 ft. The average yield was 2.82% nickel. In the Khudyakoosk iron mine, on the Ufalei estate, 4 samples yielded 0.08 to 0.11% nickel, and 0.02 to 0.04% copper. In the Staro-Cheremshansk mine, N.W. of Nijni-Karkadinsk, limonite occurs, which contained 0.95% nickel. It is found in quartzite and talcose schists, with serpentine to the west. Some serpentine, alongside the Agardiyash iron mine on the Kyshtim estate, contained green nickel ore, which assayed up to 5% nickel.

At the Tunkinsk mine, in the Serguinsk district, N.W. of Nijni-Karkadinsk, limonite occurs to a depth of 150 ft. and siderite below that depth. Boring samples, representing 40,000 tons of ore, averaged 0.75% nickel, and a concentrate gave 6.28% nickel.

SPAIN

Nickel ores exist in the Malaga serpentines of Spain and their occurrences have been described by Fritz Gillman [58].

About the year 1850 nickel ore of the garnierite (or silicate type) was discovered in the decomposed serpentine of Los Jarales near Carratraca. Soon after, the high price of nickel induced considerable local activity in the development of these deposits, and some shipments of ore were made. Later, an Englishman acquired some claims in the district, and erected

a blast furnace to smelt the ore locally, but, for reasons unknown, this proved unsuccessful. Similar ores were afterwards discovered in the Sierra Alpujata near Ojen, but the New Caledonian discoveries resulted in lowering the price of nickel to a point which ceased to be profitable to the Spanish nickel miners, and production ceased in 1894. No data are available to show the average value in nickel of the ore deposits of this district, but from the failure to compete with the New Caledonian producers, it may be inferred that this was not high.

The ores originally mined were secondary minerals, and consisted chiefly of green silicates of magnesium and nickel, the latter constituent ranging from 1 to 20%.

These ores form small irregular masses and veins in decomposed serpentine; alone, or associated with decomposed norite or augite. Below the decomposed zone the primary nickel mineral is niccolite (NiAs), and it occurs in three distinct associations, which may be termed (*a*) the chromite type, (*b*) the augite type and (*c*) the norite type.

The chromite type is a mixture of rough crystals, or more or less rounded grains of chromite, in which niccolite occurs as a cementing material. The proportion of niccolite varies, but samples may contain up to 20% nickel.

The augite type is characterized by dark greenish-brown augite in prismatic crystals, irregularly distributed and cemented together either by niccolite or by niccolite and chromite.

The norite type may be described as relatively fresh metalliferous portions of otherwise highly decomposed norite veins in the serpentines. They form tenacious kernels or nuclei in and between which appear grains and aggregations of niccolite and chromite. In the richer specimens the niccolite constitutes a ground mass around the crystals, and in a few instances the niccolite and chromite assume a more or less banded structure.

The quantity of profitable ore in the Malaga deposits does not appear large, so far as exploration has disclosed it, but inasmuch as these deposits are scattered over an area roughly 40 miles in length by 17 miles in width, the possibilities of further discoveries of ore are by no means remote.

SWEDEN

Small deposits of nickel ore similar in character to those found in Norway, occur at Klefva in Småland, at Kusa in Dalarne, and at Ruda in Ostergötland, Sweden.

For the 10 years ending 1879, the average annual production of nickel ore is given as 4,319 metric tons. During the late war, production appears to have been resumed according to the following series of outputs of ore [59]:

	1914	1915.	1916	1917.	1918.	1919.
Metric tons . .	156	1,642	3,561	4,991	2,480	416

A report in *Dagens Nyheter* that smelting furnaces were being erected at Klefva in Småland and at Kusa in Dalarne for treating these nickel ores lacks confirmation. It is improbable that Sweden's resources of nickel ore will permit of a large output.

SWITZERLAND

Nickel and cobalt ores are found in the Gollyre and Grand Praz mines near Ayer, in the Val d'Anniviers, Switzerland [60].

An ore averaging 3 to 4% nickel, 7 to 8% cobalt and 2 to 3% bismuth is said to occur at Kaltenburg in Turtmanntal, but presumably no large quantity of ore of this quality can be obtained [22/p. 246].

YUGO-SLAVIA

No important deposits of nickel ores have as yet been discovered in Yugo-Slavia. Millerite, associated with galena, is found in some quantity, here and there, in the Mt. Avala lead mines. The lead-ore deposits occur at the contact of Cretaceous limestones with intrusive rhyolite. Small quantities of the same mineral occur in association with some zinc ores in the Zavlaka zinc-lead deposits, which form irregular pockets and veins in Triassic limestone in proximity to intrusive trachyte. Millerite has also been recorded in association with intrusive serpentines in Palæozoic rock at Sadyevats, near Ivanjitsa [61].

ASIA

ASIATIC TURKEY

An occurrence of nickel ore in narrow veins in dolomite in the vilayet of Kastamuni in Asiatic Turkey was reported some years ago [62]. More recently, it has been announced that nickel ore deposits are found also at Aidin. The former deposit is at Ak-Kaya, about 60 miles from the Black Sea, and during the war was said to have been worked by the Turkish Ministry of War. The output of ore obtained was sent to German and Austrian steel works, but no information is available as to the quantities of ore produced or the nickel contents. It is suggested however that the grade of the ore is low, and that possibly the recent production was a war emergency measure, rather than an economic one [63].

CHINA

One of the first known nickel alloys was of the nickel-silver type known as *pakfong*, which has long been used in China for various domestic purposes. This alloy is said to be smelted from nickeliferous copper ore, mixed with ores of tin, lead and zinc, but no particulars of the Chinese method of manufacture are available [64].

According to *Finance and Commerce* (Shanghai) [65], nickel ores are known in three regions in China. Ores consisting of gersdorffite and niccolite occur in the gneiss, slate and quartz rocks of S.E. Yun-nan. Nickel minerals associated with galena have been found in the Tungehwan region, and, associated with cobalt, the metal appears to exist in ores in the Red River district to the west of Kochiu.

Near Wei-ning in N.W. Kwei-chow, ores containing nickel and bismuth minerals in association have been examined, and nickel has also been found in Shen-si.

In none of these cases has there been any systematic examination of the deposit.

DUTCH EAST INDIES

Borneo

On the Dutch island of Sebuk, off the coast of Borneo, a large surface deposit of nickeliferous chromiferous iron ore

occurs. This is found overlying serpentine, and averages about 15 ft. in thickness. A great part of the deposit lies along and near the sea-shore facing the channel which divides the island from its larger neighbour, the island of Laut.

The deposit has been well prospected by pits and drill holes, and extends for four miles parallel to the coast, rising from the sea-level to a ridge in places 300 ft. high. There is no overburden, but the deposit is to some extent grown over with timber. The quantity of ore is estimated to be at least 300 million tons, and the following table of analyses made on many samples taken and grouped, indicates the composition of the ore [1/pp. 265-7]:

Mixed Ore.					From 0 to 6 ft	From 6 to 9 ft	From 9 to 13 ft.
<i>Calcined</i>					%	%	%
Iron	.	.	.	.	61.30	60.30	60.69
<i>Dried</i>							
Iron	.	.	.	.	53.09	50.01	51.69
Silica	.	.	.	.	2.75	2.35	2.30
Manganese	.	.	.	.	0.43	0.37	1.05
Sulphur	.	.	.	.	0.21	0.12	0.19
Phosphorus	.	.	.	.	0.06	0.037	0.029
Chromium	.	.	.	.	2.30	2.20	2.05
Cobalt and Nickel	.	.	.	.	0.39	0.41	0.45

It will be seen from this table that, in composition, the ore bears a close resemblance to ore of the same type found and mined in Cuba for the production of "mayari" steel, and it should therefore be valuable. There is a coal mine owned by the Dutch Government on the adjacent island of Laut, and there appears to be a possibility of the ores being smelted locally.

The island of Sebuku is only just off the eastern trade routes to Europe, and practically on the fair weather cargo route from England to Australia, via Singapore.

Celebes

According to reports published in the *Board of Trade Journal* [66], some important discoveries of nickel ore and of nickeli-ferous iron ore of the lateritic type have been made in the Dutch possession of Celebes.

There are several deposits of this ore, and it is said that the latest investigations point to the existence of about 1,000 million tons of the iron ore.

About 70 borings have been sunk through the deposits at various points, and the following analyses throw light upon the composition of the ore :

Sample No	8.	9.	10.	11.
	%	%	%	%
Loss on ignition	17.28	13.02	6.81	14.01
Silica	0.42	0.82	1.40	0.76
Ferric oxide ¹	71.74	75.07	83.37	75.79
Manganese dioxide	1.40	0.99	0.98	0.85
Alumina	9.12	7.36	5.54	6.83
Nickel oxide	0.41	1.00	0.32	0.28
	100.37	98.26	98.42	98.52
¹ Iron content	50.17	52.50	58.30	53.00

Much of this ore is said to contain chromite as well as nickel, and in its general character it closely resembles the chromiferous and nickeliferous iron ores of Cuba.

The deposits occur near Larona on the Melila River, by which transport to the coast is practicable.

In addition to these iron ores considerable quantities of rich nickel ore have been reported in the same district.

It is believed that both kinds of ores arise from the peridotite and serpentine rocks.

The nickel ores agree in character with those of New Caledonia and, like the latter, fill fissures in the friable country rock, and also occur as ore crusts overlying the upper weathered strata.

The amount of nickel present is as high as 10% in certain cases, but the general average is considerably lower.

The quantity of nickel ore is estimated at 50 to 60,000 tons, but it is expected that this estimate would be increased by further exploration [67].

JAPAN

The Satsuma nickel deposits in Japan proved to be of small extent and are no longer being worked. They occur in the

marginal zone of a serpentized diorite intrusive into sedimentary rocks of Mesozoic age. Magnetite and pyrrhotite are abundant; chalcopyrite, arsenopyrite and niccolite occur in smaller amounts, while galena, blende and pyrite are rare. The gangue consists of quartz, calcite and serpentine. Mikio Kuhara believes that the earlier minerals—magnetite, pyrrhotite, chalcopyrite and niccolite—have crystallized from molten magma, whilst the later ones have been introduced in solution in hot water. But, as J. E. Spurr points out, it is possible—even probable—that the serpentine had a certain amount of independent crystallization aside from its replacing the older silicates. Accordingly, for “rock silicates” in the mineral sequence given below, “serpentine” should be substituted, which obviates the necessity for the violent assumption that the minerals which crystallized earlier than serpentine were crystallized from a molten magma, those later deposited by hot waters. All are parts of the fabric of the same limited ore-bodies.

The age of the mineralization is held to be the close of the Mesozoic. From microscopic examination of the ores, Kuhara believes the sequence of minerals to be magnetite, pyrrhotite, chalcopyrite, niccolite, rock silicates, calcite, arsenopyrite, pyrrhotite, chalcopyrite, quartz and pyrite. Strong faulting followed the mineralization.

PHILIPPINE ISLANDS

In the island of Mindanao, in the Philippine Islands, are found deposits of chromiferous iron ore similar to the Cuban and Borneo lateritic deposits described elsewhere (*see* pp. 66 and 57). The estimated quantity of this ore is about 400 million tons. The presence of nickel had not been confirmed at a recent date, but there is reason to believe that a portion, at any rate, of the ore in these deposits will prove nickeliferous like others of this type [68].

NEW CALEDONIA

Second in importance to the Canadian (Sudbury) deposits,

but much less in magnitude, are the nickel deposits of New Caledonia. They were discovered by Garnier in 1865, but nickel was not known to occur in commercial quantity till 1874 [I/p. 242].

Geologically, the island is made up of ancient schists and Mesozoic sedimentary rocks, and an extensive series of igneous rocks. Included in the last are large masses of peridotite, which has undergone hydration to a large extent and become converted into serpentine. These serpentinized peridotites stretch along the mountain chain from the S.E. portion of the island towards the N.W. end, and it is in this serpentine that the nickel occurs as garnierite, in the form of veins and concretionary masses. The unaltered olivine rock sometimes contains nickel in appreciable quantities, some samples having been reported to contain $2\frac{1}{2}\%$. The garnierite veins traversing the serpentines, however, are the source of rich ore, sometimes containing 20 to 45% nickel oxide. But there is a large area of poorer mineralized rock containing a workable percentage of nickel.

The origin of the New Caledonian nickel ore differs widely from that of the pyrrhotite ores of Sudbury. According to F. F. Sutherland, Chief Inspector of Mines for Ontario, who visited the island in 1916, the ore may best be described as an alteration product of the serpentine in which the magnesia and the iron has been replaced by nickel. When the magnesia has been so replaced, the ore formed is of a chocolate brown colour, known locally as "chocolate ore," the colour being due to oxide of iron. This is the principal kind of ore mined at present. On the other hand, when nickel has displaced the iron, the ore takes on a characteristic green colour, and is known as "green ore."

The replacement of the serpentine by nickel ore follows the joints and fractures in the serpentine, and the undecomposed blocks and boulders of serpentine are, as a rule, covered by a shell of ore, which has to be picked off. The alteration or replacement of the serpentine by nickel ore does not often extend more than 25 to 35 ft. in depth, and therefore mining is best carried on by removing the over-burden, if any, and quarrying.

The rich ore is found at or near the surface of the deposit where it occurs in the form of weathered sheets up to 20 ft. in thickness. Formerly, ore containing 12% nickel was mined for shipment, but it is now the practice to mine a mixture of ores to make a grade of about 7% nickel, after drying at 100° C.

According to E. Glasser (*Les Richesses Minérales de la Nouvelle-Calédonie*), the following represents an average analysis of a 7% ore after drying at 100° C.: Silica, 42%; magnesia, 22%; lime, 0.10%; alumina, 1%; ferric oxide, 15%; nickel oxide, 9%; cobalt oxide, 0.15%; manganese oxide, 0.70%; chromic oxide, a trace; combined water, 10%.

The mining of ore in New Caledonia began in 1875 when 300 tons were shipped. In 1876 and 1877 nearly 8,000 tons of ore containing 8 to 10% nickel were exported.

With a view to reducing freight charges by shipping a concentrated product instead of nickel ore, furnaces for reducing the ore to matte were erected at Noumea, and between 1879 and 1885 about 4,000 tons of matte were obtained and sent away. In 1885 the rate of production of nickel ore had become in excess of the demand, and the smelting furnaces remained idle until 1889. In 1891 shipments of ore and matte exceeded 54,000 tons, but by this time the discovery and exploitation of the Sudbury deposits of nickel ore began to influence the nickel market, and New Caledonian production again received a check. However, since 1897 there has been a steady production of ore and matte, representing considerably more than an average annual output of 100,000 tons of ore [69].

The production of nickel ore and matte for the five years ending 1914 in metric tons was as follows [1/p. 245]:

	1910.	1911.	1912.	1913.	1914.
Ore . . .	99,000	142,000	74,314	93,193	94,154
Matte . . .	786	2,993	5,908	5,893	5,287

The effect of the war on the New Caledonian nickel mining industry is here shown in a table of exports of ore and matte [70], [71]:

*Exports of Nickel Ore and Matte from New Caledonia with
Countries of Destination*
(Metric tons.)

Country of Destination.	1916.		1917		1918.		1919.		1920.	
	Ore.	Matte.	Ore.	Matte.	Ore.	Matte.	Ore.	Matte.	Ore.	Matte.
France . . .	7,806	783	2,880	200	12,259	400	1,509	1,000	3,246	1,671
England . . .	20,129	800	15,836	1,170	—	—	52	—	—	—
Belgium . . .	—	—	—	—	—	—	—	304	—	343
Japan . . .	2,743	—	3,276	—	3,352	—	—	—	—	—
United States . . .	—	3,352	25	4,949	—	3,537	—	2,508	—	2,494
Totals . . .	30,678	4,935	22,017	6,319	15,611	3,937	1,561	3,812	3,246	4,508

[52/1921, p. 482]

The matte contains 40 to 50% nickel.

In 1916 and 1917 the ore, as mined and smelted to matte locally, amounted to about 60,000 metric tons per year, and had a nickel content of 5.5 to 6%. The figures for 1918 and 1919 are 62,600 and 60,000 tons, respectively.

The total productions of nickel ore in New Caledonia for the years 1916-19, were as follow :

	1916	1917.	1918.	1919.
Metric tons	105,000	30,000	90,650	5,372 ¹
		¹ Exports.		

[52/1921, p. 821]

The New Caledonian ore as mined contains 20% or more of uncombined water. Drying at 100° C. appreciably reduces the weight and brings the nickel content from about 5.6% up to about 7%, but hitherto it has not been the practice to dry the ore before shipment [1/p. 247]. The advantage from a consideration of freightage of shipping dried ore, and more particularly a concentrate in the form of matte, is obvious, but such advantage may be possibly counterbalanced by the cost of importing the necessary fuel.

According to information obtained by the Ontario Nickel Commission, the freightage of nickel ore from Noumea to Hamburg in 1913, was 35 shillings per ton, and the cost of loading into ships, unloading, and transporting to smelter, 6 shillings per ton [1/p. 260].

No information is available as to the present (1923) cost of

freightage and handling the ore, but, without doubt, it largely exceeds that of 1913.

There being little or no market for New Caledonian nickel in Europe in 1921, most of the mines were obliged to close down or limit their production. A large hydro-electric plant, with capacity of 30,000 H.P., is being erected at Yate for Société le Nickel. A nickel smelting plant put up at Noumea by a Japanese company has not yet begun operations [52/1921, p. 482].

AFRICA

ABYSSINIA

As stated in the Imperial Institute monograph, *Copper Ores* (p. 138), copper and nickel ores have been found in the Walaga Province of Abyssinia, but none of them has been worked so far on a commercial scale.

EGYPT

A deposit of nickel ore of the silicate type occurs on St. John's Island in the Red Sea, and has been reported upon by Max Ismalun, through R. H. Greaves, Chief of the Department of Mines, Egypt. The description is embodied in the Report of the Ontario Nickel Commission [1/p. 270].

The nickel ore is found in a mass of peridotite, which has pierced the Tertiary beds of the island, and forms a hill about 1,000 ft. high. The peridotite contains a large number of fractures mostly filled with serpentine, but two of the larger fractures which are parallel, are filled with bands of garnierite and iron oxide, the proportion of the latter increasing with the depth, but this iron oxide is also nickeliferous. One vein has been proved for a length of 150 ft., the width varying from 2 to 5 ft., and to a depth of 120 ft. The vein material as mined averages 6.5 to 7% nickel, but the garnierite portion of the vein is said to carry 9.5% nickel, 0.4% copper and 0.1% chromium. The iron oxide portion of the vein contains 2 to 4% nickel, but the vein material is too friable to permit of any separation in mining. An analysis of a sample of ore made at the Imperial Institute resulted as follows: Nickel, 4.86%; iron, 12.25%; copper, 0.25%; insoluble, 37.59%.

The sample was also found to contain: Gold, 3 grains; platinum metals, 14.5 grains, and silver, 4 dwt. per ton.

The quantity of copper present in these ores is unusually high for this type of deposit, and the matte obtained by smelting is therefore a mixed one, from which the copper must be separated.

According to a recent official report [72], the two veins of nickel ore are immediately south of ancient and well-known peridot workings. These veins strike N.E.-S.W., are almost vertical, have an average width of $2\frac{1}{2}$ ft., and are exposed on the surface for a distance of about 165 ft. The ore occurs in green and brown alternating bands, and appears to be very similar in character to the garnierite ores of New Caledonia. The nickel content varies from 5 to 9%, the green ore being invariably richer than brown ferruginous ore. In addition to the vein matter there are on the island superficial patches of ground carrying 1 to 2.75% nickel.

The area is leased to the Red Sea Mining Co. There has been little development work, but from 5,000 to 6,000 tons of ore are estimated to be immediately available. There were trial shipments of ore to France in 1912 and 1914, amounting to 75 and 233 metric tons, respectively.

MADAGASCAR

Nickel ore deposits, similar in type to those of New Caledonia, have been known in Madagascar for some years, and, while not of very large extent, appear to be worth developing.

One deposit is at Valzoro near Ambositra in the Province of Fianarantsoa, and according to particulars supplied by A. E. Roberts, President of the Syndicat Minier de Madagascar, to the Ontario Nickel Commission, nickel ore had been proved over 82 acres in a laccolith of ultra-basic rock. This laccolith had split into a net-work of seams and cracks, along which the rock had been altered to serpentine. Nickel ore fills these cracks, which vary from a mere film to upwards of an inch in thickness [1/p. 276]. A later official report [73] states that the deposit is controlled by an English syndicate, which has not done any work upon it recently. The report also

states that the ore is easily workable at a low cost, and that water power amounting to 10,000 H.P. is available within a distance of 28 miles. Wood fuel is also abundant.

Another deposit of nickel ore of similar character in serpentine was discovered in 1917, about 15 miles east of Ambaton-drazaka on the Onibe River. Considerable development work has been done on this, and ore containing about 5½% nickel has been exposed, some samples assaying about 12%. Water power from the River Onibe and timber for fuel are available [73].

NORTH AMERICA

CUBA

The nickeliferous iron ores in the districts of Mayari, San Felipe or Cubitas, and Moa on the north coast of the island of Cuba have been known for a number of years. They are of a lateritic type, occurring as a residual mantle overlying serpentine, varying in thickness, but averaging about 19 ft. They are typical of nickeliferous iron-ore deposits in Tasmania, Greece, Spain, Celebes and Dutch Borneo. Between 1908 and 1920 inclusive, over 11 million tons of these ores were mined and shipped to the United States for the production of iron and steel [74]. The deposits are of large extent and have been estimated to contain not less than 1,600 million tons [75].

The composition of the raw ore, which contains a large percentage of both absorbed and chemically combined water, ranges in percentages as follow: Iron, 41 to 49; silica, 2 to 6; chromium, nickel and cobalt, 1.4 to 3.2; and alumina, 11 to 11.5 [76]. The possibility of separating the nickel from such material has been the subject of experiment by C. R. Hayward [77]. He finds that if the iron ore is calcined with a little pyrite or other material to form a sulphur dioxide atmosphere the nickel in the ore is converted into a soluble sulphate, which can be leached out with water, leaving a residue, which is still a good iron ore. The nickel is obtained from the solution by precipitation as hydroxide.

The ore is said to yield in smelting a nickel-chromium pig iron of special value in certain casting mixtures, and also a

low nickel-chromium steel of good grade known as "mayari" steel. Mayari steel possesses physical properties superior to those of carbon steel, and amongst other uses it has been employed as constructional material in bridging the Mississippi River at Memphis, and for other important bridges.

MEXICO

A deposit of nickel-cobalt ore was discovered in Western Chihuahua, Mexico, in 1906, but no exploitation of this has been reported.

Nickel ores occur in the Tolimán district, Querétaro. According to J. G. Aguilera [78], the nickel-bearing veins are of Tertiary age, and cut Cretaceous limestone. The nickel ore, which is in the form of oxide or arsenide (niccolite), is associated with specular iron, and yields as much as $9\frac{1}{2}\%$ nickel.

Small shipments of ore containing 30% cobalt and 7.40% nickel were made some years ago from the Esmeraldo and Pilmano mines in Jalisco. The deposits are described as occurring in small lenses in an iron formation.

Several tons of nickel-cobalt ore have been shipped from Tepic, but the deposits are stated to be too small to warrant development.

PORTO RICO

A considerable, but undefined, deposit of nickeliferous iron ore occurs west of Mayaguez in the island of Porto Rico, belonging to the United States. The deposit occurs as a mantle of bright-red earthy material overlying serpentine, from which it is considered to have been derived by weathering agencies similar to those of the well-known residual iron ores of Cuba. The serpentine area over which the ore is found is considered to have been uplifted in early Tertiary times, and the present surface now has an elevation of 1,100 to 1,200 ft. above sea-level. Considerable erosion has taken place, so that little of the original surface remains. The northern border of the serpentine area is steep, and on this side little or no covering of the decomposed materials exists and the serpentine outcrops at numerous points, but on the southern part of the area, where it slopes away at a lesser angle, the deposit attains

considerable thickness at the surface, varying in the few cases investigated from 6 to 32 ft. The material consists largely of limonite. Of eight samples analysed the maximum iron content was 46.23%, and the minimum, 17.28%, while the average was 35.6%. The ore contains both nickel and chromium, and these constituents are also present in the undecomposed serpentine [79].

The following analyses are (1) of a sample of undecomposed serpentine and (2) of a sample of the nickeliferous iron ore expressed in percentages :

	No. 1	No. 2.
Silica	38.41	2.44
Alumina	4.96	20.21
Ferric oxide	6.32	57.69
Ferrous oxide	1.27	0.85
Magnesia	33.32	0.61
Lime	0.04	trace
Sodium oxide	0.27	not determined
Potassium oxide	0.10	
Moisture	0.83	" 1.09 "
Combined water	13.40	14.96
Titanium dioxide	0.08	0.26
Nickel protoxide	0.72	1.00
Chromic oxide	0.42	1.57

SANTO DOMINGO

According to a report issued in 1918 by the United States Consul at Santo Domingo, low-grade nickel ore deposits exist at the Perseverancia mine at Sierra Prieta, 19 miles N.W. of Santo Domingo City. A considerable amount of preliminary work had been done, and a company had been organized to work the deposits [80].

UNITED STATES

In the United States there are only a few nickel deposits, and they appear to be of no great importance. Most of the nickel obtained from domestic sources in recent years, down to 1919, has been a by-product from smelting the lead ores of S.E. Missouri. In the Fredericktown district, the ore-bodies occur in the lower part of the Bonnetterre dolomite and in

the underlying La Motte sandstone. The ore consists of a mixture of lead, copper, nickel, cobalt and iron sulphides. The sulphides other than that of lead, occur in the greatest quantity in the lower part of the workings, next to, and in the sandstone, especially near the granite and porphyry. The chief source of nickel and cobalt in Missouri has been the mine of the North American Lead Co., adjoining Fredericktown. A fair amount of both metals has also come from La Motte mine of the Missouri Metals Co. in the same district. At La Motte the chief source of the nickel and cobalt was the dressed galena, which usually carries 0.2 to 0.3% of these metals. A middling product of the concentrating plant usually carried 20 to 23% lead, 0.5 to 1% copper, and 2.5 to 3.5% nickel and cobalt. A larger percentage of copper was accompanied by a correspondingly large percentage of nickel and cobalt. Besides these products of the mill, a small quantity of true nickel-cobalt ore was produced. In recent years, according to H. A. Buchler, developments in the deeper workings have disclosed the presence of extensive deposits of copper-nickel-cobalt ore [81/1918, p. 793].

From 1900 to 1906 the mine belonging to the North American Lead Co. was operated as a lead mine. In the latter years the company erected a smelter and refinery for the recovery of the lead, copper, nickel and cobalt contents of the ore. In 1909, 328,403 lb. of nickel was produced, as well as 8,314 tons of nickel and cobalt concentrate. At this time the ore-body was reported to have been 12 ft. thick, and to have carried 10% copper, 4% nickel and cobalt, and 4% lead. The company's affairs later became involved and the property remained idle until 1915, when it was taken over by the Missouri Cobalt Co. [81/1918, p. 793]. The deposits are found at the contact of sandstone and limestone (dolomite?), and are in the form of flat beds workable for a depth of 2 to 8 ft. The ore contains 2 to 2.5% copper, 0.5 to 0.8% nickel, 0.5% cobalt, together with lead and a little silver [67]. In 1919, nickel was first produced from the complex sulphides [81/1919, p. 715].

In 1920, the company produced 80,626 lb. shot nickel and 256,767 lb. nickel hydrate [81/1920, p. 405].

Nickel ores are found in Lancaster Co., Pennsylvania, and

the Gap mine in that county was for many years a producer of ore. This mine was at first considered to be a copper mine and was worked as such, but in 1862 it became the largest producer of nickel of that time. It yielded a small output of nickel regularly until 1891, when the competition from New Caledonia caused it to be closed down. The total production is given as 2,000 tons of ore, which to-day would be regarded as insignificant. The ore-body at this mine is a vertical reef up to 30 ft. in width which was mined to a depth of 250 ft. The ore minerals are pyrrhotite and chalcopyrite, and the average percentage of nickel in the ore mined is given as 1.3; that of copper being 0.25 to 0.75 and that of cobalt, 0.05 to 0.15.

Nickel sulphide ores occur at Key West mine, Nevada, where dolerite, intrusive into crystalline schists, carries sulphides of copper and nickel with some silver and platinum. The ore occurs in lenses 10 to 50 ft. thick and 50 to 100 ft. long. One deposit is estimated to contain 150,000 tons.

In Virginia, nickel occurs in a number of localities in the Piedmont region crystalline area, especially in association with many of the extensive pyrrhotite bodies of the Floyd-Carroll-Grayson plateau in the S.W. part of the State. In Amherst Co. the pyrrhotite is somewhat sparingly developed as small grains and moderate-sized granular masses, in crystalline schists, partly hornblendic, of doubtful origin. Nickel in association with peridotite masses has been reported from near Broadrun station, in Fauquier Co., Northern Virginia.

A body of nickeliferous pyrrhotite, which occurs in the extreme N.W. corner of the Floyd Co. portion of the above-mentioned plateau, has been described by T. L. Watson [85]. The ore-bearing series of rocks is of igneous origin, and intrusive in crystalline metamorphic schists, and comprises syenite, dolerite and gabbro. The nickel-bearing pyrrhotite is in mica-gabbro and has pyroxene-syenite on the foot-wall and olivene-dolerite on the hanging-wall. The dolerite and gabbro seem to be later in age than the syenite, which they apparently penetrate in dyke-like form. The ore comprises pyrrhotite chiefly, and a little intermingled chalcopyrite. It is largely

secondary, and was formed after the metamorphism of the rocks. Microscopic sections showed that the sulphides followed principally the lines of weakness in the silicate minerals, with considerable replacement of these. It is probable that the ore was the work of ascending solutions derived from great depth.

An American company worked the deposit for several years from 1904. The principal workings, known as the Lick Fork openings, comprise shafts and drifts, less than 100 ft. below water-level, aligned in a general N.E.-S.W. direction for a distance of $4\frac{1}{2}$ miles. In May, 1907, there was a large amount of ore on the dumps, which was reported to average 1.75% nickel and a fraction of 1% copper. The ore also contains a little cobalt.

At the Webster mine, Jackson Co., North Carolina, a hydrous silicate of nickel and magnesium occurs in weathered dunite. It contains less than 2% nickel and its utility is said to be limited to the possible direct production of a nickel steel from the ore. A similar deposit, discovered in 1864, occurs at Riddles, near Roseburg, in Southern Oregon [3/pp. 114-5], and up to 1896 about 3,000 tons of ore containing some 5% nickel had been produced [47/p. 962]. The country-rock is a saxonite or harzburgite containing 0.10% nickel oxide (NiO). The olivine separated from this rock contained 0.20% nickel, and from this mineral the nickel silicates were doubtless formed. Two analyses of the nickel silicates from Riddles gave: Nickel oxide, 27.57 and 29.66%; silica, 44.73 and 40.55%, respectively [86].

At the Gem mine, in Fremont Co., Colorado, there is a copper-bearing vein in which, at a depth of from 15 to 20 ft., nickel with some cobalt was quite prominent. From the surface to a depth of 75 ft. the vein had an average width of 3.5 to 4 ft.; it then pinched out, with the exception of a narrow streak of ore, but contained the same nickel and cobalt minerals, which were accompanied by native silver, specimens being occasionally so permeated by fine wire silver as to be broken with difficulty. In 1882, 12 tons of ore, containing 12% nickel and from 2 to 2.5% cobalt, with considerable chalcocite, were shipped. Later, about half a ton of selected

ore, containing 34% nickel and 3 to 4% cobalt, was sent to Swansea, England. The company owning the mine, however, was involved in litigation, and the ore-body was seemingly too small for any extended mining operations [87].

In the Monte Cristo mine, near Wickenburg, Arizona, niccolite and chloanthite, with some gersdorffite, are associated with rich primary native silver ores. These and a few other minerals, having a gangue of calcite and siderite, occur as replacement veins in granite gneiss, probably of pre-Cambrian age, intruded by dykes of pegmatite and dolerite. Annabergite (nickel bloom), erythrite (cobalt bloom) and limonite are among the secondary minerals [88].

Exports of Nickel, Nickel Oxide and Matte by the United States ¹

(1,000 lb units)

Country Importing	1913.	1914	1915.	1916.	1917	1918	1919	1920	1921
Belgium . . .	1,719	1,230	210	—	—	—	442	595	—
France . . .	4,197	4,419	3,210	1,871	2,336	2,233	1,346	73	—
Germany . . .	2,346	11,081	1,036	—	1,168	—	—	5	—
Italy . . .	1,075	1,277	2,365	1,880	5,471	5,101	526	—	—
Netherlands . .	9,164	2,376	22	139	506	—	57	—	—
Russia (in Europe)	7	186	4,082	5,371	4,917	—	—	—	—
United Kingdom .	9,213	7,604	16,352	14,087	15,845	7,803	747	70	—
Japan . . .	5	2	308	597	288	2,064	583	352	104
Other Countries .	155	720	2,014	1,705	474	268	109	120	322
Totals . . .	27,881	28,895	29,599	25,650	31,005	17,469	3,810	1,215	426

The values of the Exports of Nickel Manufactures were respectively

1913	1914	1915	1916.	1917.	1918	1919	1920	1921.
\$59,755	79,680	492,518	2,590,297	1,893,859	2,152,692	2,412,287	1,875,991	—

¹ *Foreign Commerce and Navigation of the United States*: Years 1913 to 1917 inclusive ending June 30; Years 1918-21 ending December 31

It will be seen by the above table that the distribution of nickel varied greatly during the war years owing to military requirements and to circumstances connected with the war, but prior to 1914, the United Kingdom, the Netherlands, France and Germany were the chief importing countries. The comparatively large quantity of nickel shipped to the Netherlands was doubtless, to a large extent, re-exported to other European countries.

SOUTH AMERICA

BRAZIL

According to Horace E. Williams [82/p. 195], nickel occurs near Villa de Livramento, Minas Geraes, Brazil, in a rock rich in olivine, largely altered to serpentine, which has been intruded into nepheline-syenite. At the outcrop the mineral is present as garnierite. Samples gave $3\frac{1}{2}$ to 15% nickel.

Nickeliferous pyrrhotite has also been reported from Minas Geraes, but has never been worked.

CHILE

On a mountain named Pajonales, in the department of Copiapó, Atacama, west of the silver region of Chañarcillo, the shallow parts of many lodes afforded much silver ore, which at greater depths was replaced by the ores of nickel and cobalt [83].

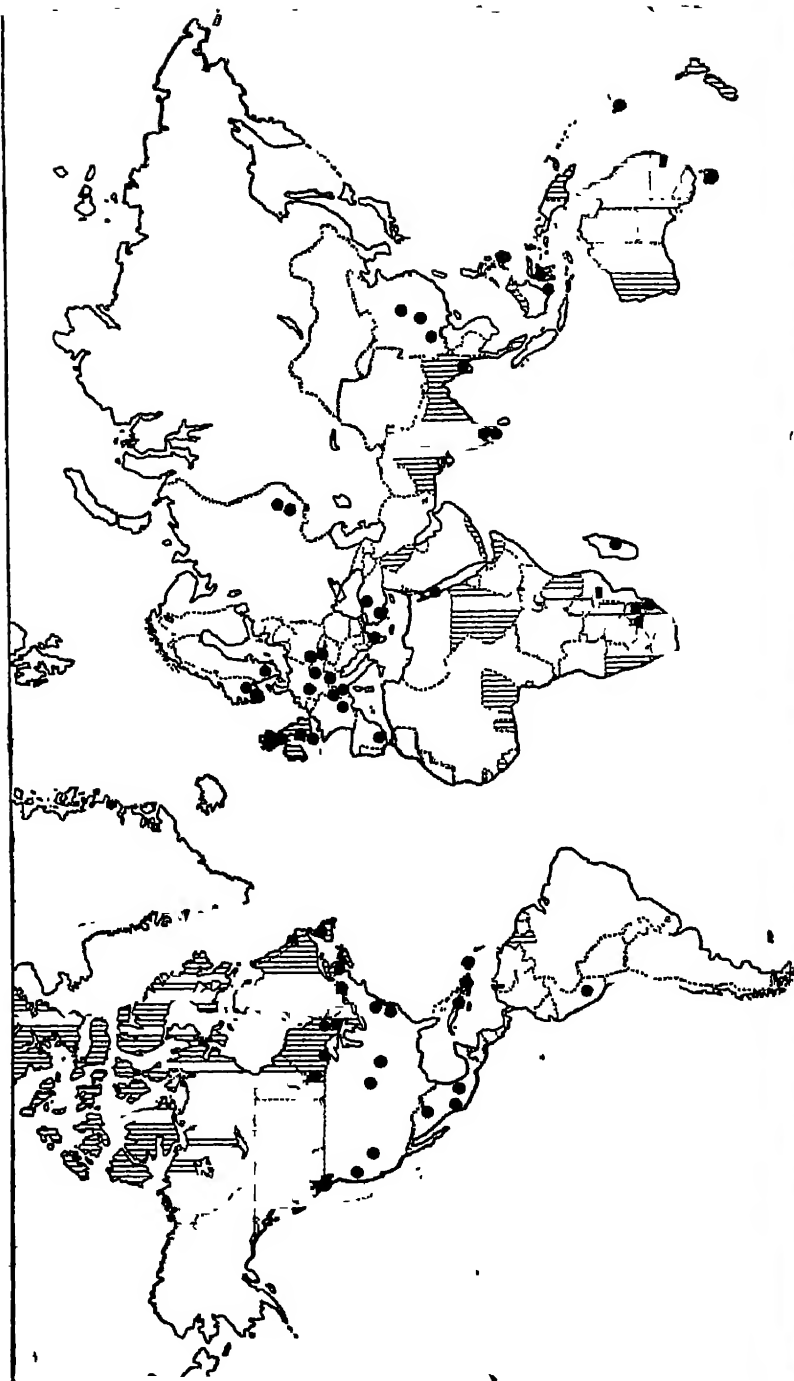
PERU

In the Vilcabamba district, Cuzco, Peru, there is a group of nickel- and cobalt-bearing veins in limestone. The principal filling is calcite and niccolite; less abundant are gersdorffite, smaltite, cobaltite, pyrite, tetrahedrite and galena [82/p. 458].

At Rapi, Ayacucho, Cuzco, the formation consists of limestones, sandstones and quartzites resting on a diorite massif, and cut by dykes of rhyolite, while masses of serpentine are in association with nickel-cobalt ores. There are a number of veins having a general strike N. of W., and a width of 2 to 4 ft. The nickel minerals are niccolite, which occurs in kidneys, gersdorffite, ullmannite and annabergite. The cobalt minerals are cobaltite and smaltite. These minerals are associated with native silver, argentite, tetrahedrite and occasionally pyrargyrite. The gangue consists of quartz, mangano-calcite and calcite. Pyrite and chalcopyrite also occur. The average of several samples gave by assay: Silver, 49 oz. per ton; nickel, 26%; cobalt, 1.8% [82/p. 466].

These veins do not appear to have been worked, no doubt owing to their inaccessibility.


 LIBRARY



MAP SHOWING THE NICKEL-BEARING LOCALITIES REFERRED TO IN THE TEXT.
(Dotted Lines Shaded)

REFERENCES TO LITERATURE ON NICKEL

The Publications are referred to by Numerals in the Text.

General

- [1] *Rept. of the Royal Ontario Nickel Commission*, Toronto, 1917.
- [2] *Ann. Rept. Ontario Bur. Mines*, 1918, Pt. 1.
- [3] Coleman, A. P. : "The Nickel Industry," *Canada Dept. Mines, Mines Branch*, 1913.
- [4] *Bull.* 695, *U.S. Geol. Survey*, 1920, p. 702.
- [5] Miller, W. G. : "Cobalt-Nickel Arsenides and Silver," *Ann. Rept. Ontario Bur. Mines*, 1913, Pt. 2, p. 8.
- [6] "The Mining and Smelting Operations of the International Nickel Co. of Canada, Ltd." (written by the Staff), *Bull.* 99, *Canadian Inst. Min. and Met.*, July 1920, pp. 546-82 ; *Bull.* 100, Aug. 1920, pp. 614-54.
- [7] *Min. Jour.*, July 23, 1921, p. 549.
- [8] Gibson, T. W. : "Nickel," *Mineral Industry*, New York, 1918, p. 513.
- [9] Anon. : "Nickel as a Catalyst in the Enrichment of Water Gas," *Times Eng. Suppl.*, Nov. 1920, p. 347.
- [10] "Some Nickel Alloys," *Met. Indus.*, July 28 and Aug. 11, 1922.
- [11] Guillet, Léon : "Nickel Brasses," *Chem. and Met. Eng.*, Feb. 9, 1921, p. 261.
- [12] *Metals and Alloys-Tables*, *Metal Industry*, London, 1920.
- [13] "Ferro Alloys and Alloy Steels," *Bull.* 9, *Advisory Council of Sci. and Indus. Comm. of Australia*, 1919.
- [14] *Quin's Metal Handbook and Statistics*, London (annual).

Great Britain

- [15] Collins, J. H. : "Observations on the West of England Mining Region," *Trans. Roy. Geol. Soc. Cornwall*, 1912, 14, pp. 341-2.
- [16] Hill, J. B., and MacAlister, D. A. : "The Geology of Falmouth and Truro and of the Mining District of Camborne and Redruth," *Memoirs Geol. Survey England and Wales*, 1906, p. 179.

- [17] Davies, D. C.: *A Treatise on Metalliferous Minerals and Mining*, London, 6th ed., 1901.
- [18] *Colliery Guard.*, March 5, 1920, p. 676.
- [19] *Indus. Australian and Min. Stand.*, May 20, 1920, p. 694.
- [20] Wilson, G. V.: "The Lead, Zinc, Copper and Nickel Ores of Scotland," *Special Rept. on the Min. Res. Great Britain, Mem. Geol. Survey, Scotland*, 1921, 17.

India

- [21] Holland, T. H., and Fermor, L. L.: "Nickel," *Rec. Geol. Survey, India*, 1915, 46, p. 281.

Nyasaland

- [22] Imperial Institute: "The Occurrences and Utilization of Nickel Ores," *Bull. Imp. Inst.*, 1916, 14, pp. 228-53.

Union of South Africa

- [23] Goodchild, W. H.: "The Economic Geology of the Insizwa Range," *Trans. Inst. Min. and Met.*, 1916, 26, p. 14.
- [24] Du Toit, A. L.: "Report on the Copper-Nickel Deposits of Insizwa," *15th Ann. Rept. Geol. Commission, Cape of Good Hope*, 1910, pp. 111-42.
- [25] Du Toit, A. L.: "The Geology of Part of the Transkei," *Union S. Africa, Geol. Survey*, 1917, p. 25.
- [26] Trevor, T. G.: "Nickel," *Bull.* 26, *Indus. Bulletin Series* (Pretoria), 1919, pp. 9-12.
- [27] Ortlepp, J. A.: "Investigations on the Copper-Nickel Ores of the Rustenburg District," *Jour. Chem. Met. and Min. Soc., S. Africa*, Aug. 1922, pp. 23-31.
- [28] Trevor, T. G.: "Notes on the Occurrence of Nickel in the Barberton District," *S. African Jour. Indus.*, June 1920, p. 532.
- [29] *South African Min. Jour.*, Feb. 19, 1921, p. 675.
- [30] Gray, C. J.: *Report on the Mining Industry of Natal for 1899*, Pietermaritzburg, p. 21.

Canada

- [31] *Ann. Repts. on the Mineral Production of Canada, Canada Dept. of Mines, Mines Branch.*
- [32] Baker, M. B.: "Alexo Nickel Mine, Timiskaming District," *Ann. Rept. Ontario Bur. Mines*, 1917, pp. 258-74.

- [33] Cross, J. G. : " The Shebandowan Nickel-Copper Deposits," *Canadian Min. Jour.*, May 5, 1922, p. 270.
- [34] *Eng. and Min. Jour.*, Oct. 8, 1921, p. 590.
- [35] Ellis, R. W. : *Summ. Rept., Geol. Survey, Canada*, 1903, pp. 156-9A.
- [36] Colony, R. J. : " A Norite of the Sudbury Type in Manitoba," *Bull. Canadian Inst. Mines*, Nov. 1920, pp. 862-72.
- [37] Del, J. S. : " Nickel Ore in Manitoba," *Bull. Canadian Inst. Min. and Met.*, Dec. 1920, p. 899.

Newfoundland

- [38] Howley, J. P. : *Mineral Resources of Newfoundland*, St. Johns, 1909, p. 8.

Australia

- [39] Pittmann, E. F. : *Min. Res. of New South Wales, Geol. Survey, New South Wales*, 1901.
- [40] White, A. G. : " Tasmanian Nickel Deposits," *Min. Mag.*, Feb. 1915, p. 103.
- [41] Waller, G. A. : *Rept. to Secretary of Mines, Tasmania*, 1902, pp. 64-6.
- [42] Twelvotrees, W. H., and Ward, L. Keith : " The Ore-Bodies of the Zeehan Field," *Bull. 8, Geol. Survey, Tasmania*, 1910, p. 52.

New Zealand

- [43] Ulrich, G. H. F. : *Quart. Jour. Geol. Soc.*, 1890, 48, pp. 619-32.
- [44] Lindgren, W. : *Mineral Deposits*, New York, 1913, p. 746.

Austria

- [45] Anon. : *Min. Jour.*, Feb. 8, 1922, p. 144.
- [46] Phillips, J. A. (H. Louis) : *A Treatise on Ore Deposits*, 2nd ed., London, 1896.
- [47] Beyschlag, Vogt, and Krusch (Truscott) : *The Deposits of the Useful Minerals and Rocks*, London, 1914, 2 vols.
- [48] Dörler, G. : *Bilder von den Kupferkies-Lagerstätten bei Kitzbühel*, Vienna, 1890, pp. 7-14.

Czechoslovakia

- [49] Beck, R. (W. H. Weed) : *The Nature of Ore Deposits*, New York, 1905, 2 vols.

France

- [50] Rickard, T. A.: "Notes on Deposits of Chalanches, France," *Trans. Am. Inst. Min. Eng.*, 1894, **24**, p. 424.
- [51] Henwood, W. J.: "On the Mines of Chalanches D'Allemont in France," *Trans. Roy. Geol. Soc. Cornwall*, 1871, **8**, pp. 517-29.
- [52] *Mineral Industry*, New York (annual).

Germany

- [53] Anon.: *Min. Jour.*, Aug. 14, 1920, p. 630 (abs. from *Das Berg*).

Greece

- [54] Scott, H. K.: "Chromiferous Iron Ores of Greece," *Jour. Iron and Steel Inst.*, 1913, **87**, Pt. 1, pp. 447-67.

Norway

- [55] Smith, H. H.: "Note on the Skorovas Iron Pyrites Deposit, Norway," *Bull. 217, Inst. Min. and Met.*, 1922, p. 4.

Russia

- [56] Anon.: "Russian Nickel Deposits," *Eng. and Min. Jour.*, Nov. 6, 1915, p. 759.
- [57] Turner, H. W.: "Nickel Deposits in the Urals," *Trans. Am. Inst. Min. Eng.*, 1914, **48**, pp. 118-24.

Spain

- [58] Gillman, F.: "Notes on the Ore Deposits of the Malaga Serpentine (Spain)," *Trans. Inst. Min. and Met.*, 1896, **4**, p. 159.

Sweden

- [59] *Nat. Fed. Iron and Steel Manufacturers, Stat. Rept.*, 1918, p. 55.

Switzerland

- [60] Anon.: "Nickel Deposits in Switzerland," *Zett. prakt. Geologie*, 1909, **17**, p. 271.

Yugo-Slavia

- [61] Wray, D. A.: *The Geology and Mineral Resources of the Serb-Groat-Slovene State*, Dept. Overseas Trade, 1921, pp. 46, 65 and 66,

Asiatic Turkey

- [62] Aston, J.: "Nickel and Cobalt," *Mineral Industry*, 1913, p. 524.
- [63] Penzer, N.: "The Minerals of Anatolia," *Min. Mag.*, Nov. 1919, p. 279.

China

- [64] Read, T. T.: "Mineral Production and Resources of China," *Trans. Am. Inst. Min. Eng.*, 1912, 43, pp. 3-53.
- [65] Anon.: "Nickel Ores in China," *Canadian Chem. and Met.*, Feb. 1922, p. 43.

Dutch East Indies

- [66] *Bd. Trade Jour.*, 1918, Oct. 3, p. 436; Nov. 14, p. 615; and Nov. 21, p. 651.
- [67] Anon.: "New Source of Nickel Ore," *Min. Jour.*, May 1, 1920, p. 328.

Philippine Islands

- [68] Pratt, W. E.: "The Iron Ores of the Philippines," *Trans. Am. Inst. Min. Eng.*, 1915, 53, pp. 90-105.

New Caledonia

- [69] Anon.: "Three Companies Operating in New Caledonia," *Eng. and Min. Jour.*, July 3, 1920, p. 20.
- [70] Gibson, W. T.: "Nickel," *Mineral Industry*, 1919, p. 486.
- [71] Miller, W. S.: "Mineral Production of New Caledonia," *Canadian Min. Jour.*, April 15, 1920, p. 305.

Egypt

- [72] *Report on the Mineral Industry of Egypt*, Cairo, 1922, pp. 26-7.

Madagascar

- [73] Anon.: "Étude Succincte sur les Mines de Madagascar en 1920," *Bull. Écon. de Madagascar*, 1920, Pt. 1, p. 19.

Cuba

- [74] Cone, E. F.: "Iron and Steel," *Mineral Industry*, 1920, p. 385.
- [75] Spencer, A. C.: "Occurrence, Origin and Character of the Surficial Iron Ores of Camaguey and Oriente Provinces, Cuba," *Trans. Am. Inst. Min. Eng.*, 1911, 51, pp. 230-7.

- [76] Hayes, C. Willard · "The Mayari and Moa Iron Ore Deposits in Cuba," *Trans. Am. Inst. Min. Eng.*, 1911, **42**, pp. 109-15.
 [77] Hayward, C. R. · "Extraction of Nickel and Alumina from Cuban Iron Ores," *Chem. and Met. Eng.*, Feb. 8, 1922, pp. 261-6.

Mexico

- [78] *The Mexican Year Book*, London, 1909-10, p. 486.

Porto Rico

- [79] Fettke, C. R., and Hukkard, Bela · "Limonite Deposits of Mayaguez, Mesa, Porto Rico," *Trans. Am. Inst. Min. Eng.*, 1918-19, **61**, pp. 97-112.

Santo Domingo

- [80] Anon. · "Development of Dominican Nickel Deposits," *U.S. Comm. Rept.* 236, Oct. 8, 1918, p. 99.

United States

- [81] *Mineral Resources of the United States*, U.S. Geol. Survey (annual).

Brazil

- [82] Miller, B. L., and Singewald, J. T.: *The Mineral Deposits of South America*, New York and London, 1919.

Chile

- [83] Henwood, W. J.: "The Mining District of Chañarcillo, in Chile," *Trans. Roy. Geol. Soc. Cornwall*, **8**, 1871, p. 121.

ADDENDA

- [84] *Prel. Rept. Min. Production of Canada during the Six Months ending June 30, 1922*, Ottawa, 1922.
 [85] Watson, T. L.: "The Occurrence of Nickel in Virginia," *Trans. Am. Inst. Min. Eng.*, 1907, **38**, pp. 683-97.
 [86] Clark, F. W.: *Data of Geochemistry*, 4th ed., New York, 1920, pp. 700-2.
 [87] Barlow, A. E.: "Report on the Nickel and Copper Deposits in the Sudbury Mining District," *Canada Geol. Survey, Ann. Rept.* (new series), 1901, **14**, H, p. 179.

- [88] Bastin, E. S. : " Primary Native Silver Ores near Wickenburg, Arizona, and their bearing on the Genesis of the Silver Ores of Cobalt, Ontario," *Bull.* 735E, *U.S. Geol. Survey*, 1922, p. 154.
- [89] Cook, H. C. : " Resources of Rice Lake and Oisau River Areas, Manitoba," *Summ. Rept. Geol. Survey, Canada*, 1921, Pt. C, p. 26.
- [90] McCann, W. S. : " The Maskwa River Copper-Nickel Deposit, Southeastern Manitoba," *Summ. Rept. Geol. Survey, Canada*, 1920, Pt. C, p. 19.
- [91] Wadhams, A. J. : " The Nickel Industry in 1921-1922," *Indus. and Eng. Chem.*, Apr. 1923.



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